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The Theory of the Herschel-Quincke Tube

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A former discussion of the theory of the Herschel-Quincke tube is continued and supplemented by the investigation by Professor H. S. Uhler of a more general case. With the areas of the bifurcated conduits different, it is found that the number of frequencies giving zero transmission is again more numerous than determined by the condition of a difference of phase corresponding to that of one-half wave-length in the two branches. In the more general case the former fixed relations between these phase differences no longer holds. They are now connected by the equality

$$S_2 \sin \alpha_3 = -S_3 \sin \alpha_2,$$

where S_2 and S_3 are the areas and α_2 and α_3 the phase differences in the corresponding branches.

IN 1930[1] the writer published a discussion of the theory of the Herschel-Quincke tube.[2] It was therein assumed that the tube "consists of a branched conduit constructed with constant total cross-sectional area." A conduit of area S_1 is bifurcated into branches of areas S_2 and S_3, which are reunited in a single conduit of area $S_4=S_1$. In the treatment it was assumed that $S_1=S_2+S_3$ and $S_2=S_3$. For almost a century it had been believed that these critical frequencies were explained by a difference of path of one-half wave-length in the two branches. Clearly the waves meeting at the distant junction would be in opposition in phase and equal in amplitude. The variation in pressure would be zero and no wave would enter conduit 4. But no one had given any attention to the fact that the two waves continued on around through the branches. The discussion in 1930[1] showed that if α_2 and α_3 are the changes in phase in branches 2 and 3, respectively, then the conditions for zero transmission were $\alpha_2-\alpha_3=(2n+1)\pi$ and $\alpha_2+\alpha_3=2n\pi$, where n is any positive integer. The former condition was the well-known one, but the latter was new.

The foregoing assumptions are, in fact, less general than the conditions with the tubes of Quincke.[2] He used branches of equal areas, $S_2=S_3$ but there was no special stipulation in regard to S_1 and S_4, the area of all the conduits being apparently the same.

[1] G. W. Stewart, Phys. Rev. **31**, 4 (1928).
[2] Herschel, Phil. Mag. **3**, 401 (1833); Pogg. Ann. **31**, 245 (1834); Quincke, Pogg. Ann. **128**, 177 (1866).

In 1931, Professor H. S. Uhler of Yale University obtained the power transmission, P, for a more general case. He has recently communicated to me his result with permission to publish. He found for $S_1=S_4$ but with S_2 and S_3 entirely general,

$$P=4(r_2\sin\alpha_3+r_3\sin\alpha_2)^2/ \\ [(1+r_2^2+r_3^2)\sin\alpha_2\sin\alpha_3 \\ +2(1-\cos\alpha_2\cos\alpha_3)r_2r_3]^2 \\ +4[r_2\sin\alpha_3\cos\alpha_2 \\ +r_3\sin\alpha_2\cos\alpha_3], \qquad (1)$$

where $S_2/S_1=r_2$ and $S_3/S_1=r_3$. The condition for $P=0$ becomes

$$S_2\sin\alpha_3+S_3\sin\alpha_2=0. \qquad (2)$$

When $S_2=S_3$, (2) reduces to the condition in the former paper which may be expressed as

$$\sin\tfrac{1}{2}(\alpha_3+\alpha_2)\cos\tfrac{1}{2}(\alpha_3-\alpha_2)=0. \qquad (3)$$

If $S_2\neq S_3$, such as when the value of $\sin\alpha_3$ is a fraction of that of $\sin\alpha_2$ and opposite in sign, values of α_3 can always be found that will satisfy (3) for any value of α_2, but there is no fixed relation between them as formerly obtained for $S_2=S_3$. It is somewhat surprising that zero transmission or $P=0$ may occur with two branches of different areas, but this is because the result does not depend upon the equal division of any incoming wave into two waves of equal intensities. As already noted the transmission involves a complexity of waves.

Only viscosity will prevent cases of zero transmission with branches of different areas. An experimental test with one area say twice the other would prove interesting. The theory, in assuming plane waves in the conduits, infers that the diameters are small in comparison with a wave-length. Consequently the effects of viscosity cannot be indefinitely reduced by increasing the diameters of the conduits.

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A General Theory of Passive Linear Electroacoustic Transducers and the Electroacoustic Reciprocity Theorem. I*

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(Received August 1, 1945)

A theory of the operation of passive linear electroacoustic transducers is developed on the basis of the most general linear equations (in this case, integral equations) relating the pressure and normal velocity at each point on the transducer surface and the voltage and current at the transducer's electrical terminals. These, together with the appropriate solutions of the wave equation expressed through the use of Green's functions for the medium in which the transducer is immersed and the equations defining the electrical termination of the transducer, completely characterize the behavior of the transducer and allow explicit calculation of such quantities as impedances, responses, etc., in terms of four parameters entering the fundamental equations.

On the basis of this theory, a proof of the reciprocity theorem for electroacoustic transducers relating their speaker and microphone responses is presented embodying the conditions necessary for its validity. These conditions are essentially the existence of certain symmetry relationships among the transducer parameters. When these symmetry relationships may be expected to hold is to be discussed in Part II of this paper to appear later. Some applications of the theory are presented and others are outlined.

1. INTRODUCTION

IN spite of the great importance of passive linear electroacoustic transducers in modern acoustical investigations, no general theoretical treatment of such transducers has to the author's knowledge, appeared in the literature. What work has been done on the subject has been largely confined to the discussion of particular transducers or of particular transducer elements (coupling mechanisms, diaphragms, etc.) or has consisted of approximating a general transducer by a four-terminal electrical network (electromechanical network) with force and velocity replacing voltage and current at one pair of terminals. In such treatments the actually distributed parameters of the transducer are often treated as lumped, and in addition the radiation reaction on the transducer is considered as a lumped parameter (the radiation impedance); hence, the treatment is valid only for a particular mode of motion of the diaphragm, which seriously limits the generality of the results so obtained. In particular the electroacoustic reciprocity theorem can only be proved for special cases by this method.

To remedy this treatment, one must consider a transducer to have not one or a finite number of degrees of mechanical freedom but a nondenumerably infinite number. In the present paper this generalization is made, leading to linear integral equations rather than algebraic equations governing the behavior of the transducer. From these equations, one can calculate quite generally various quantities of interest concerning the transducer in different environments, such as responses, impedances, etc., in terms of several parameters characteristic of any particular transducer. In Part I of this paper, we assume that the behavior of a passive linear electroacoustic transducer can be represented by linear integral equations and prove the electroacoustic reciprocity theorem under the assumption of certain relations among the transducer parameters. In Part II of this paper we shall indicate the proof that transducers actually are governed by such equations and establish sufficient conditions for the existence of the relationships between the transducer parameters which lead to the electroacoustic reciprocity theorem.

The existence of reciprocity theorems for mechanical, elastic, acoustical, and electromagnetic systems has been known for a long time and these theorems have been discussed by various authors.[1] The electroacoustic reciprocity

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[1] See, for example, Lord Rayleigh, *Theory of Sound* (The Macmillan Company, New York, 1937), Vol. I,

theorem is of more recent origin and seems to have been first enunciated by Schottky[2] in 1926. It has further been discussed by Ballantine and especially by MacLean,[3] who have also indicated how it may be applied to the absolute calibration of electroacoustic transducers by purely electrical measurements. It is this latter application which gives the electroacoustic reciprocity theorem a position of special importance. The reciprocity theorem states that, at least for a large class of passive linear electroacoustic transducers, the ratio of the microphone response of the transducer to its speaker response is a quantity which is independent of the nature and construction of the transducer. The proof of this theorem as given by Schottky and MacLean cannot be considered valid since it is based on an assumption which has not only never been proved, but is not generally valid as we shall show. The reciprocity theorem itself is not always valid (one can, in fact, construct transducers which do not obey the theorem)[4] but sufficient conditions which are of considerable generality can be given for its validity.

2. FUNDAMENTAL EQUATIONS FOR PASSIVE LINEAR ELECTROACOUSTIC TRANSDUCERS

2.1 Fundamental Transducer Equations

An electroacoustic transducer is a device for transforming electrical power into acoustical power, or, *vice versa*, acoustical power into electrical power. If all the power delivered by the transducer to the electrical or acoustical systems to which it is connected is derived from power absorbed by the transducer from these systems, the transducer is said to be passive. This does not prohibit the presence of active internal sources of power such as are used to provide polarizing or magnetizing voltages or currents in some types of transducers, provided that these internal sources do not supply power to the electrical or acoustical systems to which the transducer is connected. The carbon transmitter or a transducer containing internally an electronic amplifier, however, cannot be considered as passive transducers.

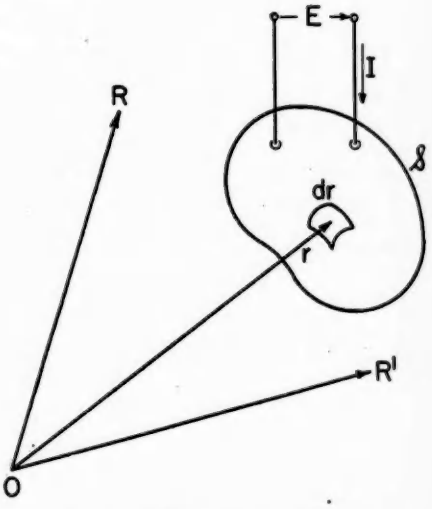

FIG. 1. Schematic transducer in an infinite medium capable of propagating sound.

Schematically, a transducer may be represented as a pair of electrical terminals to which connection to electrical systems is made and a closed surface which is in contact with a medium capable of propagating sound forming the acoustical system to which the transducer is connected. The acoustically active surface of the transducer may form only a part of the closed external surface of the transducer, but this can be automatically taken care of in the equations which we shall develop.

The following notation will be adopted (See Fig. 1): The transducer will generally be considered to be immersed in a medium capable of propagating sound which will be assumed to be infinite in extent, continuous, homogeneous, and isotropic. We shall assume that the medium is a fluid so that it is capable of propagating longitudinal waves only and hence can be completely characterized by its density ρ and its sound velocity c. The theory, as we shall indicate, can be readily generalized to cases where the medium does not have these properties, but the above covers most cases of theoretical and practical interest. We shall specify any point in the

pp. 93 ff and 150 ff, Vol. II, pp. 145 ff; A. E. H. Love, *A Treatise on the Mathematical Theory of Elasticity* (Cambridge University Press, Cambridge, England, 1927), pp. 173 ff; P. Frank and R. v. Mises, *Die Differential- und Integralgleichungen der Mechanik und Physik* (Friedrich Vieweg und Sohn, Braunschweig, Germany, 1935), Vol. II, pp. 953 ff.

[2] Schottky, Zeits. f. Physik **36**, 689 (1926).

[3] S. Ballantine, Proc. I. R. E. **17**, 929 (1929). W. R. MacLean, J. Acous. Soc. Am. **12**, 140 (1940).

[4] This seems to have first been shown by E. M. McMillan. See also Part II of the present paper, to appear in a later issue.

medium by its radius vector $\mathbf{R}$ from an arbitrary origin. A point on the surface of the transducer which we shall represent by $\mathfrak{S}$ will be designated by its radius vector from the same origin and will be denoted by a small letter $\mathbf{r}$. An element of area of the surface about the point $\mathbf{r}$ will be denoted by $d\mathbf{r}$. The pressure and particle velocity at any point will be denoted by $p(\mathbf{R}, t)$ and $\mathbf{v}(\mathbf{R}, t)$, where t is the time, while the normal velocity on the surface $\mathfrak{S}$ will be denoted by $v_n(\mathbf{r}, t)$.

The quantities of interest in our discussion are then the voltage $E(t)$ across the electrical terminals of the transducer, the current $I(t)$ flowing into these terminals, the acoustic pressure and velocity at any point in the medium $p(\mathbf{R}, t)$ and $\mathbf{v}(\mathbf{R}, t)$, and the pressure and normal velocity $p(\mathbf{r}, t)$ and $v_n(\mathbf{r}, t)$ at any point on the surface $\mathfrak{S}$ of the transducer.

In general, all of the above quantities will vary with time. We shall consider only the steady-state single frequency case in which all of the quantities vary harmonically with time with the same frequency. They may then be written using the complex notation:

$$\begin{aligned} E(t) &= Ee^{i\omega t}, & I(t) &= Ie^{i\omega t}, \\ p(\mathbf{R}, t) &= p(\mathbf{R})e^{i\omega t}, & \mathbf{v}(\mathbf{R}, t) &= \mathbf{v}(\mathbf{R})e^{i\omega t}, \\ p(\mathbf{r}, t) &= p(\mathbf{r})e^{i\omega t}, & v_n(r, t) &= v_n(\mathbf{r})e^{i\omega t}. \end{aligned} \tag{1}$$

Cases in which the time variation is not harmonic can be treated by the usual method of Fourier analysis into harmonic components since the equations which we shall develop will all be linear and hence the principle of superposition can be applied.

It is not obvious that the transducer can be characterized by relations between the quantities E and I at its electrical terminals and the values of $p(\mathbf{r})$ and $v_n(\mathbf{r})$ on the surface of the transducer alone, but we shall show in Part II of the present paper that this is generally the case. In addition, it is observed, and will be shown in Part II to follow from theoretical considerations, that any two of the above quantities can be varied independently and the values of the other two are then dependent upon these. This means than if we choose I and $v_n(\mathbf{r})$ as the independent variables, the fundamental equations for the transducer consist of equations relating E and $p(\mathbf{r})$ to I and $v_n(\mathbf{r})$. A *linear* passive electroacoustic transducer is characterized by the fact that these equations are linear in these variables for all frequencies. The most general equations of this type which can be written are the following

$$p(\mathbf{r}) = \int_{\mathfrak{S}} z_0(\mathbf{r}, \mathbf{r}')v_n(\mathbf{r}')d\mathbf{r}' + h(\mathbf{r})I, \tag{2}$$

$$E = \int_{\mathfrak{S}} h'(\mathbf{r}')v_n(\mathbf{r}')d\mathbf{r}' + Z_b I, \tag{3}$$

where $z_0(\mathbf{r}, \mathbf{r}')$, $h(\mathbf{r})$, $h'(\mathbf{r}')$, and Z_b are independent of $p(\mathbf{r})$, $v_n(\mathbf{r}')$, E, and I but are, in general, functions of the frequency. These equations are the natural generalization of a set of simultaneous linear algebraic equations, such as obtain for an electromechanical transducer with many pairs of "mechanical" terminals to the case where the number of "mechanical terminals" becomes non-denumerably infinite. The ordinary concept of linearity as associated with electrical network theory is maintained in these equations, and it is because of this linearity that the principle of superposition holds.

To indicate the connection between the theory of electroacoustic transducers and the theory of electromechanical transducers, it is interesting to rewrite Eqs. (2) and (3) for the case where the normal velocity at each point on the surface is the same. The normal velocity can then be taken outside the integrals in the equations giving

$$p(\mathbf{r}) = v_n \int_{\mathfrak{S}} z_0(\mathbf{r}, \mathbf{r}')d\mathbf{r}' + h(\mathbf{r})I, \tag{4}$$

$$E = v_n \int_{\mathfrak{S}} h'(\mathbf{r}')d\mathbf{r}' + Z_b I. \tag{5}$$

If the first equation is integrated over the surface and the integral of the pressure called F, the force, one obtains

$$F = \zeta_0 v_n + \eta I, \tag{6}$$

$$E = \eta' v_n + Z_b I, \tag{7}$$

where

$$\zeta_0 = \int_{\mathfrak{S}}\int_{\mathfrak{S}} z_0(\mathbf{r}, \mathbf{r}')d\mathbf{r}'d\mathbf{r}, \tag{8}$$

$$\eta = \int_{\mathfrak{S}} h(\mathbf{r}')d\mathbf{r}', \tag{9}$$

$$\eta' = \int_{\mathfrak{S}} h'(\mathbf{r}')d\mathbf{r}'. \tag{10}$$

Eqs. (6) and (7) will be recognized as the equations for an electromechanical transducer, having the same form as the equations for a four terminal electrical network.[5]

[5] The argument as given here is not rigorous, but may be made so. One should show that it is possible to arrange the transducer parameters, $z_0(\mathbf{r}, \mathbf{r}')$, $h(\mathbf{r})$, $h'(\mathbf{r}')$, and Z_b, such that the normal velocity is always uniform over the surface, that is, independent of $\mathbf{r}'$. This can be done by inverting Eqs. (2) and (3), that is, solving them for $v_n(\mathbf{r}')$ and I in terms of $p(\mathbf{r})$ and E. It will then be evident that if $z_0(r, r')$, $h(\mathbf{r})$, and $h'(\mathbf{r}')$ are independent of $\mathbf{r}$ and $\mathbf{r}'$,

Whether or not, for any particular electroacoustic transducer, Eqs. (2) and (3) are valid can only be determined by a theoretical or experimental analysis of the transducer. It is known, however, that for the majority of passive transducers now in use, these equations are satisfied for limited ranges of the variables, this range of variation being known as the linear range of the instruments. It is this fact that makes this class of instruments worthy of special study.

In accordance with usual terminology, we shall refer to an electroacoustic transducer which is converting electrical power to acoustical power as a speaker, and we shall refer to one which is converting acoustical power to electrical power as a microphone.

2.2 The Transducer Parameters

It will be noted from Eqs. (2) and (3) that the transducer is completely characterized by the four parameters Z_b, $h(\mathbf{r})$, $h'(\mathbf{r})$, and $z_0(\mathbf{r}, \mathbf{r}')$ when these are known as a function of frequency. This characterization is independent of the medium in which the transducer is immersed. To understand the physical significance of these parameters, consider first the case where the transducer diaphragm is blocked so that $v_n(\mathbf{r}) \equiv 0$; then Z_b is just the ratio of E to I or the *blocked electrical impedance* of the transducer. On the other hand $h(\mathbf{r})$ is then just the ratio of $p(\mathbf{r})$ to I. This quantity is just analogous to a transfer impedance in electrical circuit theory; we shall therefore refer to it as the *speaker transfer parameter*. If we now consider the case where the electrical terminals of the transducer are open-circuited, so that I is zero, then we see that $h'(\mathbf{r})$ is also a transfer parameter and we shall refer to it as the *microphone transfer parameter*. Finally, it will be noted that when $I=0$, the parameter $z_0(\mathbf{r}, \mathbf{r}')$ relates in a general way the pressure and normal velocity at various points on the diaphragm and has the dimensions of acoustic impedance; we shall therefore refer to it as the *generalized open-circuit normal acoustic impedance* of the transducer surface.

In so far as the linearity of a transducer is concerned there are no restrictions on the values which the transducer parameters may take. However, certain restrictions will be placed on these quantities in order that such principles as the law of conservation of energy are satisfied for the transducer. To determine the values of the parameters for a particular transducer, it would be necessary to study in detail the construction and mode of operation of the transducer theoretically or experimentally. This is, for all except very simple transducers, a difficult task.

However, on examining actual transducers, one finds that in many cases important relationships exist between the transducer parameters. Of particular interest are the reciprocity relationships which may be written

$$h(\mathbf{r})/h'(\mathbf{r}) = e^{i\alpha}, \tag{11}$$

$$z_0(\mathbf{r}, \mathbf{r}') = z_0(\mathbf{r}', \mathbf{r}), \tag{12}$$

with α a real constant independent of $\mathbf{r}$. The first equation simply states that $h(\mathbf{r})$ and $h'(\mathbf{r})$ are equal in magnitude and the phase angle between them is the same at all points of the transducer surface. The reciprocity relationships (11), (12) are not universally true of all transducers, since it is known that one can construct transducers which do not obey these conditions. They are, however, either true or at least approximately true of a great many, probably of a majority, of transducers now in use. The importance of these relationships lies in the fact that a transducer for which they hold obeys the electroacoustic reciprocity theorem (which we shall derive below) and consequently can be used in an absolute acoustic calibration by the reciprocity method.

Hence, it would be highly desirable to be able to determine, preferably theoretically, whether or not a particular transducer obeys the reciprocity relationships. Unfortunately, there does not seem to exist any universal criterion; to a certain degree each transducer must be studied individually. It should be noted that a similar situation exists in regard to the proof of all reciprocity theorems, such as the reciprocity

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that is, constants, then the normal velocity will be the same at all parts of the transducer surface. It will also be found possible to arrange the parameters so that the normal velocity is constant over a part of the surface and zero elsewhere, or so that the velocity at any point on the surface is always proportional to the velocity at one fixed point.

theorems for elastic media, the electromagnetic field, etc.[1] In all these proofs it is assumed that the material media present behave in some prescribed way, such as, for example in the electromagnetic case, that the material media can be described in the conventional sense by a scalar conductivity, dielectric constant, and permeability. In an analogous fashion, the validity of the reciprocity conditions for a transducer will depend upon the nature of the materials employed in its construction and the mechanism by which the electromechanical coupling is established.

We shall reserve for Part II of the present paper the detailed discussion of some of the conditions under which the reciprocity relations are valid for an electroacoustic or electromechanical transducer. Here we need only state that transducers in which only one of the following types of electromechanical coupling: electrostatic, piezoelectric, electromagnetic, magnetostrictive, are employed, or in which a combination of the first two types, or the last two types only, are used, generally obey the reciprocity conditions unless dissipation phenomena of a rather unusual character are present in the elastic, dielectric, piezoelectric, magnetic, or magnetostrictive media employed in their construction. It should also be pointed out, that while Eq. (12) appears to be a consequence of the well known reciprocity theorem for mechanical systems, this is illusory since, in general, the value of $z_0(\mathbf{r}, \mathbf{r}')$ will depend on the electromechanical coupling mechanism as well as the purely mechanical parameters of the transducer.

2.3 Acoustical Center and Axis

In the following discussion it will sometimes be convenient to refer to an acoustical center and an acoustical axis for the transducer. For our purposes, the acoustical center of a transducer may be defined as any point having a fixed geometrical position with regard to the transducer. Its position is quite arbitrary, but in practice is often selected to be a point most closely approximating the center of the spherical sound waves produced by the transducer at large distances, or the geometrical center of the transducer. The acoustic axis is arbitrary in a similar fashion, and may be taken as any axis through the acoustic center of the transducer. In practice it is often selected as some symmetry axis of the transducer or as the axis of maximum response. When we speak of the transducer being placed at some point with its axis oriented in some direction, it will be meant that the acoustical center is placed at the point and the acoustic axis oriented in the given direction.

2.4 Coupling to the Transducer

In operation an electroacoustic transducer is coupled on its electrical side to other electrical elements and on its acoustical side to a medium which may or may not contain sound sources. The two principal types of coupling on the electrical side are coupling to an impedance load or to an electrial source. When a transducer is referred to as terminated on its electrical side in an electrical load impedance Z_l, it is meant that the following relationship between E and I obtains:

$$E = -Z_l I, \tag{13}$$

while if it is referred to as connected to a source of impedance Z_l and generated voltage E_g, it is meant that the following relationship holds:

$$E = E_g - Z_l I. \tag{14}$$

The problem of coupling on the acoustical side is more complicated. In general, the medium to which the diaphragm is coupled demands a certain relationship between $p(\mathbf{r})$ and $v_n(\mathbf{r})$. Let us consider first, the case when the diaphragm is in contact with an infinite homogeneous isotropic medium of density ρ and sound velocity c, with no sources present in the medium. In order to do this we must have some means of expressing the pressure at any point in the medium in terms of the normal velocity distribution on the surface of the transducer. This may very conveniently be accomplished, without specifying the nature of the surface $\mathfrak{S}$, by the use of Green's functions.[6] It can be shown that for any closed surface $\mathfrak{S}$ of sufficient regularity,

[6] For general references on Green's functions, the following may be consulted: P. Franck and R. v. Mises, *Die Differential- und Integralgleichungen der Mechanik und Physik* (Friedrich Vieweg und Sohn, Braunschweig, Germany, 1935), Vol. II, pp. 803 ff; H. Bateman, *Partial Differential Equations of Mathematical Physics* (Cambridge University Press, Cambridge, England, 1932), p. 140; A. Sommerfeld, Jahr. d. B. Math. Verein. 21, 309 (1912).

there exists a function $G(\mathbf{R}, \mathbf{R}')$ which has the following properties: It satisfies the wave equation

$$\nabla_{\mathbf{R}'}^2 G(\mathbf{R}, \mathbf{R}') + k^2 G(\mathbf{R}, \mathbf{R}') = 0, \quad k = \omega/c, \tag{15}$$

at every point outside the surface $\mathfrak{S}$ except at the point $\mathbf{R}' = \mathbf{R}$ where it has a singularity (pole) of the form

$$G(\mathbf{R}, \mathbf{R}') \rightarrow \frac{1}{|\mathbf{R} - \mathbf{R}'|}, \quad \mathbf{R}' \rightarrow \mathbf{R}. \tag{16}$$

Asymptotically as $\mathbf{R}' \rightarrow \infty$, this function behaves like

$$A \exp(-ik|\mathbf{R} - \mathbf{R}'|)/|\mathbf{R} - \mathbf{R}'|, \tag{17}$$

(where A is a function only of the direction of $\mathbf{R} - \mathbf{R}'$ and not of its magnitude), and on the surface $\mathfrak{S}$ it satisfies the condition

$$\partial G(\mathbf{R}, \mathbf{R}')/\partial n]_{\mathbf{R}' \text{ on } \mathfrak{S}} = 0. \tag{18}$$

Such a function is known as a Green's function and it can be shown to have the additional important property that it is symmetric in the variables $\mathbf{R}$ and $\mathbf{R}'$, that is,

$$G(\mathbf{R}, \mathbf{R}') = G(\mathbf{R}', \mathbf{R}). \tag{19}$$

The physical interpretation of a Green's function of the type described is quite simple: It may be interpreted as the pressure produced at the point $\mathbf{R}'$ by a point source of sound waves of unit strength placed at the point $\mathbf{R}$ in the presence of the surface $\mathfrak{S}$ when the latter is completely rigid. From the symmetry of the Green's function, there follows the reciprocity theorem for the sound field, namely, that the pressure produced at the point $\mathbf{R}'$ by a point source of unit strength at the point $\mathbf{R}$ is the same as the pressure which would be produced at the point $\mathbf{R}$ if the same point source were located at the point $\mathbf{R}'$.

By the use of Green's theorem, one can now show that if $p(\mathbf{R})$ is a function satisfying the wave equation without sources in the region outside of the surface $\mathfrak{S}$, having no singularities in this region, and behaving like $B \exp(-ik|\mathbf{R}|)/|\mathbf{R}|$ at infinity (with B a function of the direction of $\mathbf{R}$ only, and not of its magnitude), which means that it represents outgoing waves, then $p(\mathbf{R})$ can be expressed as a surface integral over the surface $\mathfrak{S}$ in the following manner:

$$p(\mathbf{R}) = \frac{1}{4\pi} \int_{\mathfrak{S}} G(\mathbf{R}, \mathbf{r}') \partial p(\mathbf{r}')/\partial n \, d\mathbf{r}', \tag{20}$$

where $\partial p/\partial n$ represents the normal derivative of p on the surface (the normal being taken positive when directed into the surface $\mathfrak{S}$). We may now take $p(\mathbf{R})$ to be the pressure in the medium, and remembering that the particle velocity in the medium is given by

$$\mathbf{v}(\mathbf{R}) = \frac{i}{\omega\rho} \nabla p(\mathbf{R}), \tag{21}$$

so that

$$v_n(\mathbf{r}) = \frac{i}{\omega\rho} \partial p(\mathbf{r})/\partial n, \tag{22}$$

we obtain the following equation for the pressure in the medium as a function of the normal velocity distribution on the surface $\mathfrak{S}$:

$$p(\mathbf{R}) = -\frac{i\omega\rho}{4\pi} \int_{\mathfrak{S}} G(\mathbf{R}, \mathbf{r}') v_n(\mathbf{r}') d\mathbf{r}'. \tag{23}$$

As an example of a Green's function of the type described, for a simple case, we may give the function for the case of an infinite plane (which may be considered closed by a surface at infinity which gives no contribution to the surface integral). If in Fig. 2, $\mathbf{R}''$ is the image of the point $\mathbf{R}$ in the plane $\mathfrak{S}$, then the Green's function can be written as

$$G(\mathbf{R}, \mathbf{R}') = \frac{\exp(-ik|\mathbf{R} - \mathbf{R}'|)}{|\mathbf{R} - \mathbf{R}'|} + \frac{\exp(-ik|\mathbf{R}'' - \mathbf{R}'|)}{|\mathbf{R}'' - \mathbf{R}'|}. \tag{24}$$

It is evident that the normal derivative of the Green's function vanishes on the plane, and if one represents the image of $\mathbf{R}'$ in the plane by $\mathbf{R}'''$, the symmetry of the Green's function becomes obvious. If $\mathbf{R}'$ is taken to be a point $\mathbf{r}'$ lying on the plane, we have

$$G(R, \mathbf{r}') = \frac{2 \exp(-ik|\mathbf{R} - \mathbf{r}'|)}{|\mathbf{R} - \mathbf{r}'|}, \tag{25}$$

and thus if $v_n(\mathbf{r}')$ is the normal velocity distribution on the plane

$$p(\mathbf{R}) = -\frac{i\omega\rho}{2\pi} \int_{\mathfrak{S}} v_n(\mathbf{r}') \frac{\exp(-ik|\mathbf{R} - \mathbf{r}'|)}{|\mathbf{R} - \mathbf{r}'|} d\mathbf{r}', \tag{26}$$

which will be recognized as the usual formula for finding the pressure at any point when the velocity distribution on the plane is given.

The Green's functions for only a few surfaces are known and, except for the case of the plane, they are, in general, complicated infinite series. This does not, however, diminish the usefulness of the Green's function as a means of expressing solutions of the wave equation satisfying certain boundary conditions. The mere existence of the Green's function for the surface $\mathfrak{S}$ and the fact that it is symmetrical in its variables is all that is required in the analysis which follows in this paper.

If in Eq. (23), we now let the point $\mathbf{R}$ approach the point $\mathbf{r}$ on the surface of the transducer, we

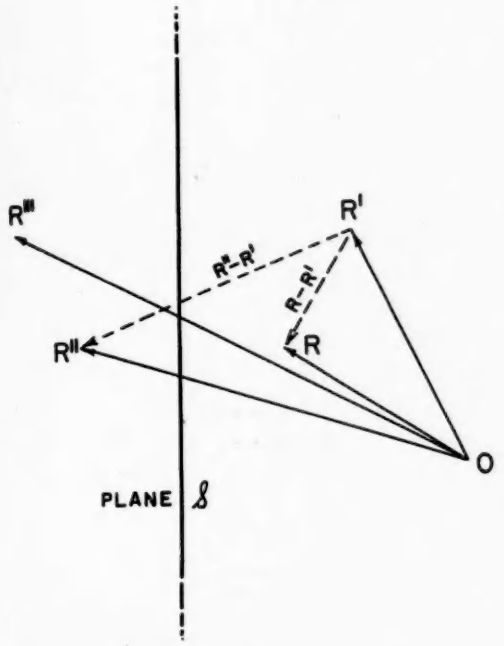

FIG. 2. Notation for Green's function for an infinite plane.

obtain the desired relationship between the pressure and normal velocity on the surface of the transducer when no sources are present in the medium:

$$p(\mathbf{r}) = -\frac{i\omega\rho}{4\pi}\int_{\mathfrak{S}} G(\mathbf{r},\mathbf{r}')v_n(\mathbf{r}')d\mathbf{r}'. \qquad (27)$$

From its analogy with Eq. (13), this equation indicates that

$$z_r(\mathbf{r},\mathbf{r}') = \frac{i\omega\rho}{4\pi}G(\mathbf{r},\mathbf{r}') \qquad (28)$$

represents a sort of generalized acoustic impedance of the medium, which may be referred to as the generalized acoustic radiation impedance of the transducer in the medium.

When sources are present in the medium (and we shall assume them sufficiently distant so that the transducer can still be considered to be present in an infinite medium), then even in the absence of the transducer from the medium there will be a pressure wave in the medium which we may represent as $p_0(\mathbf{R})$. If $p(\mathbf{R})$ is the pressure distribution in the medium when the transducer is introduced, we can write by Eq. (20)

$$p(\mathbf{R}) - p_0(\mathbf{R}) = \frac{1}{4\pi}\int_{\mathfrak{S}} G(\mathbf{R},\mathbf{r}') \times [\partial p(\mathbf{r}')/\partial n - \partial p_0(\mathbf{r}')/\partial n]d\mathbf{r}', \qquad (29)$$

since $p(\mathbf{R})-p_0(\mathbf{R})$ certainly has no singularities outside of the surface $\mathfrak{S}$. Making use of Eq. (22), we obtain, if $\mathbf{r}$ is taken to be a point on the surface of the transducer

$$p(\mathbf{r}) = p_0(\mathbf{r}) - \frac{1}{4\pi}\int_{\mathfrak{S}} G(\mathbf{r},\mathbf{r}')\partial p_0(\mathbf{r}')/\partial n d\mathbf{r}' - \frac{i\omega\rho}{4\pi}\int_{\mathfrak{S}} G(\mathbf{r},\mathbf{r}')v_n(\mathbf{r}')d\mathbf{r}'. \qquad (30)$$

This is the desired relationship. We see that (28) now acts as an internal generalized acoustic impedance of the medium considered as a generator of pressure on the transducer surface. The "generated pressure" of the medium, however, is not $p_0(\mathbf{r})$ but is given by the sum of the first two terms on the right of Eq. (30). The second term represents the diffraction pressure which would result if the transducer surface were rigid, while the third term is the "pressure drop" caused by the motion of the transducer surface.

Considering again the special case where the velocity $v_n(\mathbf{r})$ is a constant over the surface of the transducer, one may obtain the pertinent coupling relationships by integrating Eq. (27) and Eq. (30) over the surface of the transducer. This yields

$$F = -\left[\frac{i\omega\rho}{4\pi}\int_{\mathfrak{S}}\int_{\mathfrak{S}} G(\mathbf{r},\mathbf{r}')d\mathbf{r}'d\mathbf{r}\right]v_n, \qquad (31)$$

or

$$F = \left[\int_{\mathfrak{S}} p_0(\mathbf{r})d\mathbf{r} - \frac{1}{4\pi}\int_{\mathfrak{S}}\int_{\mathfrak{S}} G(\mathbf{r},\mathbf{r}')\partial p_0(\mathbf{r}')/\partial n d\mathbf{r}'\right] - v_n\frac{i\omega\rho}{4\pi}\int_{\mathfrak{S}}\int_{\mathfrak{S}} G(\mathbf{r},\mathbf{r}')d\mathbf{r}'d\mathbf{r}. \qquad (32)$$

The coefficient of v_n in (31) is just the usual mechanical radiation impedance. The term in brackets in (32) represents just the "generated force" of the medium considered as a source of mechanical power.

To generalize the results given above for coupling to an acoustic medium to the case where the medium is not infinite, homogeneous, or isotropic, one may make use of the fact that one can, in general, define a symmetric Green's function in these cases as well, which satisfies the wave equation in such a medium and any boundary conditions which may be imposed at

its bounding surfaces. The remainder of the theory then remains essentially the same.

3. CALCULATION OF TRANSDUCER CHARACTERISTICS

In the next few sections we shall indicate how the fundamental equations for electroacoustic transducers together with the equations for coupling to electrical and acoustical systems can be used to calculate characteristics of the transducer which are of direct physical interest in terms of the transducer parameters.

3.1 Impedances

The electrical and generalized normal acoustical impedances of a transducer are readily calculable. The electrical impedance is defined to be the ratio of E to I at the electrical terminals of the transducer. Its value will depend upon the characteristics of the acoustical medium in which the transducer is immersed. In the case of an infinite homogeneous medium without sources one may substitute the expression for $p(\mathbf{r})$ given in Eq. (27) into Eq. (2); rearranging terms one obtains

$$\int_{\mathcal{S}}\left[z_0(\mathbf{r},\mathbf{r}')+\frac{i\omega\rho}{4\pi}G(\mathbf{r},\mathbf{r}')\right]v_n(\mathbf{r}')d\mathbf{r}'=-h(\mathbf{r})I. \quad (33)$$

This is an integral equation of the first kind[7] for $v_n(\mathbf{r}')$. To indicate the method of solution, consider first a simple one-dimensional integral of the first kind:

$$g(x)=\int_a^b K(x,x')f(x')dx'. \quad (34)$$

In this equation $g(x)$ and $K(x,x')$ are given functions, the latter being known as the *kernel* of the integral equation, and one is to find $f(x')$. Now it can be shown that there exists another function $k(x',x'')$ of x' and x'', known as the *resolvent kernel*, such that the solution of Eq. (34) can be written as

$$f(x')=\int_a^b k(x',x'')g(x'')dx''. \quad (35)$$

The determination of the resolvent kernel will in general be a difficult task, but as in the case of Green's functions, the mere existence of such a function is all that is required for the analysis that we shall give. In a similar fashion one may show the existence of a resolvent kernel for the two-dimensional integral Eq. (33). Since a kernel and resolvent kernel are related in a sort of reciprocal manner, though they are not actual reciprocals of one another, it is convenient to adopt the notation

$$\{K(\mathbf{r}',\mathbf{r}'')\}^{-1}$$

for the resolvent kernel of the kernel $K(\mathbf{r},\mathbf{r}')$.[8] By the use of the resolvent kernel we may now give an explicit expression for the solution of the integral Eq. (33), namely

$$v_n(\mathbf{r}')=-I\int_{\mathcal{S}}\left\{z_0(\mathbf{r}',\mathbf{r}'')+\frac{i\omega\rho}{4\pi}G(\mathbf{r}',r'')\right\}^{-1}h(\mathbf{r}'')d\mathbf{r}''. \quad (36)$$

Substituting this in Eq. (3), one obtains for the electrical impedance

$$Z=\frac{E}{I}=Z_b-\int_{\mathcal{S}}\int_{\mathcal{S}}\left\{z_0(\mathbf{r}',\mathbf{r}'')+\frac{i\omega\rho}{4\pi}G(\mathbf{r}',\mathbf{r}'')\right\}^{-1}h(\mathbf{r}'')h'(\mathbf{r}')d\mathbf{r}''d\mathbf{r}'. \quad (37)$$

The first term on the right is the blocked impedance; the second term is usually referred to as the motional impedance. The impedance when the transducer surface is entirely free, that is, when the transducer is placed in a vacuum so that $p(\mathbf{r})$ is zero, can be obtained from the above by setting ρ equal to zero:

$$Z_f=Z_b-\int_{\mathcal{S}}\int_{\mathcal{S}}\{z_0(\mathbf{r}',\mathbf{r}'')\}^{-1}\times h(\mathbf{r}'')h'(\mathbf{r}')d\mathbf{r}''d\mathbf{r}'. \quad (38)$$

[7] The following are useful references on integral equations of the first kind: P. Franck and R. v. Mises, *Die Differential- und Integralgleichungen der Mechanik und Physik* (Friedrich Vieweg und Sohn, Braunschweig, Germany, 1930), Vol. I, Part III, p. 471; Whittaker and Watson, *Modern Analysis* (Cambridge University Press, Cambridge, England, 1940), Chapter XI, p. 211; Margenau and Murphy, *The Mathematics of Physics and Chemistry* (D. Van Nostrand and Company, New York, 1943), Chapter 14.

[8] Note that we shall reserve the use of braces and a negative exponent to indicate the resolvent kernel so that there need be no confusion between a resolvent kernel and an actual reciprocal.

The corresponding equation for the case where the transducer surface moves with constant velocity is readily found to be

$$Z = Z_b - \frac{\eta\eta'}{\zeta_0 + \zeta_r}, \quad \zeta_r = \frac{i\omega\rho}{4\pi}\int_{\mathcal{S}}\int_{\mathcal{S}} G(\mathbf{r}, \mathbf{r}')d\mathbf{r}'d\mathbf{r}. \quad (39)$$

The symbolic similarity between this equation and Eq. (37) is striking, and it indicates the close correspondence between the theory of electromechanical and the theory of electroacoustical transducers.

In a similar way, we may derive an equation for the generalized normal acoustic impedance of the transducer surface when the electrical terminals of the transducer are connected to an electrical load impedance Z_l. The generalized normal acoustic impedance, $z(\mathbf{r}, \mathbf{r}')$, is defined by the equation

$$p(\mathbf{r}) = \int_{\mathcal{S}} z(\mathbf{r}, \mathbf{r}')v_n(\mathbf{r}')d\mathbf{r}'. \quad (40)$$

By substituting the expression for E as given by Eq. (13) into Eq. (3) one may obtain I as a function of $v_n(\mathbf{r}')$. On substituting this into Eq. (2) one obtains

$$p(\mathbf{r}) = \int_{\mathcal{S}}\left[z_0(\mathbf{r}, \mathbf{r}') - \frac{h(\mathbf{r})h'(\mathbf{r}')}{Z_b + Z_l}\right]v_n(\mathbf{r}')d\mathbf{r}', \quad (41)$$

so that the generalized normal acoustic impedance is given by

$$z(\mathbf{r}, \mathbf{r}') = z_0(\mathbf{r}, \mathbf{r}') - \frac{h(\mathbf{r})h'(\mathbf{r}')}{Z_b + Z_l}. \quad (42)$$

The first term is the open-circuit generalized normal acoustic impedance. The short-circuit impedance may be obtained by setting Z_l equal to zero in Eq. (42). The generalized normal acoustic impedance can be used to find the effect on a sound field produced by introducing the transducer into the medium.

3.2 Responses

Of particular interest are the responses of the transducer: the speaker response relating the pressure in the sound field produced by the transducer to the current input, and the microphone response relating the voltage produced by the transducer when placed in a given sound field to the magnitude of the sound field.

Consider the case of a transducer driven by an input current I and thereby producing a pressure $p(\mathbf{R})$ in the acoustic medium at the point $\mathbf{R}$. The *speaker response* may be defined as the ratio of $p(\mathbf{R})$ to I. To obtain this quantity, we first substitute Eq. (27) into Eq. (2) which gives an integral equation of the first kind for $v_n(\mathbf{r}')$. The solution of this integral equation is Eq. (36), and on substituting this into Eq. (23), we obtain for the speaker response

$$S(\mathbf{R}) = \frac{p(\mathbf{R})}{I} = \frac{i\omega\rho}{4\pi}\int_{\mathcal{S}}\int_{\mathcal{S}} G(\mathbf{R}, \mathbf{r}')\left\{z_0(\mathbf{r}', \mathbf{r}'') + \frac{i\omega\rho}{4\pi}G(\mathbf{r}', \mathbf{r}'')\right\}^{-1} h(\mathbf{r}'')d\mathbf{r}''d\mathbf{r}'. \quad (43)$$

The determination of the microphone response is a little more difficult. We shall first calculate the voltage developed by the transducer when it is placed in a sound field with pressure distribution (before the insertion of the transducer) $p_0(\mathbf{R})$. Writing $p_g(\mathbf{r})$ for the sum of the first two terms in Eq. (30) and substituting this into Eq. (2) yields an integral equation for $v_n(\mathbf{r}')$. Solving this equation by the method of resolvent kernels and substituting the result into Eq. (3) gives the equation

$$E = \int_{\mathcal{S}}\int_{\mathcal{S}} h'(\mathbf{r}')\left\{z_0(\mathbf{r}', \mathbf{r}'') + \frac{i\omega\rho}{4\pi}G(\mathbf{r}', \mathbf{r}'')\right\}^{-1} \times [p_g(\mathbf{r}'') - h(\mathbf{r}'')I]d\mathbf{r}''d\mathbf{r}' + Z_b I. \quad (44)$$

If the transducer is electrically terminated in an impedance Z_l we may substitute $-E/Z_l$ for I in this equation and solve for E, thus obtaining

$$E = \frac{Z_l}{Z_l + Z}\int_{\mathcal{S}}\int_{\mathcal{S}} h'(\mathbf{r}')\left\{z_0(\mathbf{r}', \mathbf{r}'') + \frac{i\omega\rho}{4\pi}G(\mathbf{r}', \mathbf{r}'')\right\}^{-1} p_g(\mathbf{r}'')d\mathbf{r}''d\mathbf{r}', \quad (45)$$

which gives the voltage developed by the transducer in any type of sound field. If the transducer is open-circuited, we may make Z_l infinite, thus obtaining for the open-circuit voltage

$$E_0 = \int_{\mathcal{S}}\int_{\mathcal{S}} h'(\mathbf{r}')\left\{z_0(\mathbf{r}', \mathbf{r}'') + \frac{i\omega\rho}{4\pi}G(\mathbf{r}', \mathbf{r}'')\right\}^{-1} p_g(\mathbf{r}'')d\mathbf{r}''d\mathbf{r}'. \quad (46)$$

Consider now the case where the incident sound field $p_0(\mathbf{R})$ is a spherical wave with center at the point $\mathbf{R}_0$. If we let $\mathbf{R}_c$ be the acoustical center of the transducer, we shall define the microphone response as the ratio of the open-circuit voltage developed by the transducer in this sound field to the incident pressure at the point $\mathbf{R}_c$, that is $E_0/p_0(\mathbf{R}_c)$. Writing

$$p_0(\mathbf{R})=\Phi \exp(-ik|\mathbf{R}-\mathbf{R}_0|)/|\mathbf{R}-\mathbf{R}_0| \quad (47)$$

for the incident spherical wave, it can easily be shown by the use of Green's theorem that

$$p_\varphi(\mathbf{r}'')=\Phi G(\mathbf{r}'', \mathbf{R}_0). \quad (48)$$

This also follows immediately from the physical interpretation of the Green's function, since $p_\varphi(\mathbf{r})$ is the pressure due to a point source of strength Φ in the presence of the rigid surface $\mathfrak{S}$. On substituting this in Eq. (46), one readily obtains for the microphone response

$$\begin{aligned} M(\mathbf{R}_0)&=\frac{E_0}{p_0(\mathbf{R}_{0c})} \\ &=|\mathbf{R}_c-\mathbf{R}_0|\exp(ik|\mathbf{R}_c-\mathbf{R}_0|) \\ &\times\int_{\mathfrak{S}}\int_{\mathfrak{S}} h'(\mathbf{r}')\left\{z_0(\mathbf{r}', \mathbf{r}'') \right. \\ &\left.+\frac{i\omega\rho}{4\pi}G(\mathbf{r}', \mathbf{r}'')\right\}^{-1} G(\mathbf{r}'', \mathbf{R}_0)d\mathbf{r}''d\mathbf{r}'. \end{aligned} \quad (49)$$

The response for plane waves can be obtained from this in the limit as the point $\mathbf{R}_0$ is infinitely removed from $\mathbf{R}_c$.

3.3 Efficiencies, Directivity Index, etc.

By following the same methods which have been employed in the last two sections, one may compute other quantities of interest for transducers such as their efficiency as speakers or microphones, their directivity indices, etc. Since these calculations are quite straightforward, we shall not present them here.

4. THE RECIPROCITY THEOREM FOR ELECTROACOUSTIC TRANSDUCERS

4.1 Proof of the Reciprocity Theorem

The reciprocity theorem for electroacoustic transducers states that, for transducers satisfying the reciprocity conditions (11) and (12), the ratio of the microphone response to the speaker response is, in absolute value, a quantity which is independent of the particular characteristics of the transducer and thus the same for all transducers satisfying the above conditions. The theorem follows immediately from the Eqs. (43) and (49) if one substitutes $e^{-i\alpha}h(\mathbf{r}')$ for $h'(\mathbf{r}')$ in (49) and make use of the fact that both $z_0(\mathbf{r}', \mathbf{r}'')$ and the Green's functions, $G(\mathbf{R}, \mathbf{r}')$, $G(\mathbf{r}', \mathbf{r}'')$ are symmetric in their arguments. The ratio of $M(\mathbf{R})$ to $S(\mathbf{R})$ is then given by

$$\frac{M(\mathbf{R})}{S(\mathbf{R})}=\frac{4\pi|\mathbf{R}_c-\mathbf{R}|}{i\omega\rho}\exp(-i\alpha+ik|\mathbf{R}_c-\mathbf{R}|), \quad (50)$$

and on taking the absolute value of this quantity, one obtains the reciprocity theorem[9]

$$|M(\mathbf{R})/S(\mathbf{R})|=\frac{4\pi|\mathbf{R}_c-\mathbf{R}|}{\omega\rho}=\frac{2d}{\rho f}=\frac{2d\lambda}{\rho c}=J, \quad (51)$$

where $d=|\mathbf{R}_c-\mathbf{R}|$. Since the theorem is valid for all points $\mathbf{R}$ it follows that the directivity pattern of a transducer used as a speaker is the same as its directivity pattern when used as a microphone.

One point concerning Eq. (51) deserves clarification. It will be noted that the distance between the point $\mathbf{R}$ and the acoustic center enters explicitly into J, yet the acoustic center of the transducer can be arbitrarily selected, which may at first glance appear odd. It must be remembered, however, that the microphone response is, as we have defined it, also a function of the choice of the acoustic center (it is the ratio of E_0 to $p_0(\mathbf{R}_c)$ where $\mathbf{R}_c$ is the acoustic center) and its dependence on the choice of the acoustic center will just be compensated by the dependence of J.

4.2 Applications to the Reciprocity Method of Absolute Calibration

MacLean has indicated an ingenious method of employing the reciprocity theorem to obtain the absolute calibration of electroacoustic transducers. The method employs three transducers:

[9] It is to be noted that the proof of the electroacoustic reciprocity theorem requires the reciprocity conditions (11) and (12) and the symmetry of the Green's function (19), that is, the reciprocity theorem for the sound field.

a speaker, a microphone, and a reversible transducer; only the last must obey the reciprocity theorem. Since the procedure is clearly outlined in MacLean's paper it is unnecessary to repeat it here except to say that it requires the measurement of the voltage developed by the microphone and the reversible transducer when placed at the same point in the sound field of the speaker, the measurement of the voltage developed by the microphone in the sound field of the reversible transducer used as a speaker, and the measurement of the current into the reversible transducer in this last test. The separation of the instruments is preferably kept constant during these tests and this separation distance must also be known. It is our purpose here to point out certain observations regarding the execution of a reciprocity calibration which it is helpful to keep in mind.

Consider first the choice of the electrical terminals at which the electrical measurements are made in the test. Insofar as the speaker is concerned it is only necessary to keep the current input the same during the measurements of the voltage developed by the microphone and reversible transducer in its field. The choice of terminals for the microphone should be those at which the calibration of the microphone is desired and should be kept the same in both tests in which the microphone is involved. The terminals may if desired be selected at the output of a preamplifier associated with the microphone or at the end of a fixed length of cable or directly at the output terminals of the microphone element itself. Insofar as the reversible transducer is concerned, the choice of terminals will ordinarily be selected at the output of the transducer element itself. It will be shown in Part II of this paper, however, that if a transducer obeys the reciprocity conditions, the addition of a passive linear four-terminal electrical network to the electrical terminals of the transducer will preserve the reciprocity conditions for the transducer with the remaining two terminals of the network now regarded as the electrical terminals of the transducer. The four-terminal network may, for example, be a cable or a compensating network to flatten the frequency response of the transducer, but cannot, of course, be an electronic amplifier. Thus the choice of the electrical terminals for the reversible transducer is to a large extent arbitrary and may be selected for greatest convenience in making the tests. The essential point is, however, that the current input into the transducer when operating as a speaker be measured at the same pair of terminals at which the open-circuit voltage is measured when the transducer is operating as a microphone. While the open-circuit voltage developed by the transducer is required in the tests, one can of course measure the voltage generated across some finite load impedance provided one can determine the voltage loss thereby entailed and thus make a correction to obtain the open-circuit voltage generated.

The matter of testing geometry requires somewhat more discussion. Our proof of the reciprocity principle required the use of a point source of spherical waves. While this requirement is not essential, it is essential that whatever source is used satisfy the following requirements:

(1) It produces a sound field which is spherical over the region to be occupied by the transducer when the latter is placed in position in the medium.

(2) Its presence does not appreciably change the radiation impedance of the transducer.

(3) The radiative properties of the source are not appreciably changed by the introduction of the transducer into the medium.

This means that if a transducer is used as the source, it must be placed at a sufficient distance from the other transducer so that the above conditions are satisfied. The bearing of this on a reciprocity calibration is the following: If L is the largest dimension of any of the three instruments used in the test, the testing distance d employed in the tests should be great enough so that the following conditions are met

$$L \ll d, \quad L^2/\lambda \ll d. \tag{52}$$

When this is the case, the calibration obtained for the microphone will be essentially that for plane waves.

It should be understood, of course, that all that has been said above refers to a free-field reciprocity calibration with the tests made in what is effectively an infinite homogeneous isotropic medium.

4.3 Reciprocity Theorem for Two Transducers Coupled Through an Acoustic Medium

Schottky and MacLean base their proofs of the electroacoustic reciprocity theorem on the assumption that the four exposed electrical terminals of two transducers coupled acoustically through an acoustic medium can be considered to obey the theorem for passive electrical networks to the effect that the two transfer impedances of such a network are equal. It is therefore of interest to investigate the validity of this assumption.

If we consider two electroacoustic transducers placed in an acoustic medium at a sufficient distance apart so that the conditions (52) are satisfied, and denote by E_{I}, I_{I}, M_{I}, and S_{I} the open-circuit voltage and current at the terminals of one transducer and its microphone and speaker response, respectively, and by E_{II}, I_{II}, M_{II}, and S_{II} the corresponding quantities for the other transducer, then if transducer I is used as a speaker and transducer II as a microphone

$$Z_{\mathrm{I,II}}=\frac{E_{\mathrm{II}}}{I_{\mathrm{I}}}=M_{\mathrm{II}}S_{\mathrm{I}}, \tag{53}$$

while if transducer II is used as a speaker and transducer I as a microphone

$$Z_{\mathrm{II,I}}=\frac{E_{\mathrm{I}}}{I_{\mathrm{II}}}=M_{\mathrm{I}}S_{\mathrm{II}}. \tag{54}$$

For these two quantities to be equal one must have

$$\frac{M_{\mathrm{I}}}{S_{\mathrm{I}}}=\frac{M_{\mathrm{II}}}{S_{\mathrm{II}}}. \tag{55}$$

Now if the reciprocity conditions (11) and (12) are satisfied by both transducers with the same value of α for each, then Eq. (55) will be satisfied and the theorem on the transfer impedances follows. If the reciprocity conditions are satisfied but with different values of α for the two transducers, Eq. (55) will be satisfied for the magnitudes of the quantities but not for their phases, and hence the transfer impedances will be equal in magnitude but not in phase. Two other possibilities exist, however: Transducers can be built which will not satisfy the electroacoustic reciprocity theorem and also will not satisfy Eqs. (55), and it is possible that transducers may satisfy (55) without satisfying the reciprocity theorem. The latter would be the case for two identical transducers, which do not obey the reciprocity conditions (11) and (12), coupled to the same medium. Hence one must conclude that the reciprocity theorem on the transfer impedances is not generally valid for electroacoustic transducers and consequently that the proof of the electroacoustic reciprocity theorem given by Schottky and MacLean is not generally valid.

In Part II of this paper (which will probably appear in the January, 1946 issue of this journal), the authors will show that when the reciprocity conditions (11) and (12) hold, Eq. (55) is valid regardless of the distance between the two transducers, and not only for the large distances for which the present proof is applicable.

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Attenuation of Sound in Circular Ducts

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MOLLOY and Honigman,[1] following the theory of Morse[2] have shown how to calculate the attenuation of sound in lined cylindrical ducts. In this note an alternative method is given.

The main problem is to obtain the lowest root,—corresponding to the first mode of vibration,—$\pi(\mu+ik)$, of the equation,

$$\frac{Z}{\rho c\eta}=\frac{\pi i}{\pi(\mu+ik)}\frac{J_0[\pi(\mu+ik)]}{J_1[\pi(\mu+ik)]}, \tag{1}$$

where $Z/\rho c$ is the specific normal acoustic impedance, μ and k are Morse's distribution-parameters, J_0 and J_1 are the usual Bessel functions of the first kind, and η is the duct-diameter in wave-lengths. Once this root is found, then the attenuation (of the first mode) in db/ft. is given[2] by

$$D=\frac{.04836}{\sqrt{2}}\nu\left\{\left[\frac{(\mu^2+k^2)^2}{\eta^4}+2\frac{k^2-\mu^2}{\eta^2}+1\right]^{\frac{1}{2}}+\frac{\mu^2-k^2}{\eta^2}-1\right\}^{\frac{1}{2}}, \tag{2}$$

where ν is the frequency in c.p.s.

The method of solution is to write

$$y=\frac{\pi i}{2}\frac{\rho c\eta}{Z}, \quad w=\frac{\pi^2}{4}(\mu+ik)^2, \tag{3}$$

and expand w as a power series in y. This can be conveniently done by using the properties of the Bessel functions to derive

$$(w+y^2)(dw/dy)=w. \tag{4}$$

Substitution in (4) then gives

$$w=y-(y^2/2)+(y^3/6)-(y^4/48)-(y^5/80)+\cdots. \tag{5}$$

Also it is seen from (4), by considering $w+y^2=0$, that the radius of convergence of (5) is one-half the absolute value of the lowest root, $\pi(\mu+ik)$, of the equation,

$$J_1[\pi(\mu+ik)]=iJ_0[\pi(\mu+ik)]. \tag{6}$$

A rough interpolation in a table[3] of Bessel functions indicates that this radius $\geqslant 3.6$.

It appears that the values of y met in most cases of practice are so small that only the first three terms of the series in (5) need be considered. Then the solution reduces to

$$w=1-e^{-y}. \tag{7}$$

When w is known, Eq. (2) gives for the attenuation

$$D=.03419\nu[(A^2-2A\cos\alpha+1)^{\frac{1}{2}}+A\cos\alpha-1]^{\frac{1}{2}}, \tag{8}$$

where

$$Ae^{i\alpha}=\left(\frac{2}{\pi\eta}\right)^2 w=\left(\frac{2}{\pi\eta}\right)^2(1-e^{-y}). \tag{9}$$

Formulas (8) and (9) were tried out on two examples. The first, from Molloy and Honigman,[1] is for the attenuation at $\nu=256$ c.p.s. in a 10″-diameter duct ($\eta=.1890$) lined with 1″-thickness J. M. Sanacoustic pad. Using 7.117 and $-72.82°$ for the modulus and argument, respectively, of $Z/\rho c$, these authors compute $D=.76$ db/ft. By the present method $y=-.03985+.01232i$, and $D=.743$. The latter value of D is considered accurate.

The first case was not considered a fair test since, y being so small, the series in (5) converges very rapidly. So, with the object of increasing y, the attenuation was calculated at $\nu=1000$ c.p.s. in a 15″-diameter duct—so that $\eta=1.108$—with the same lining. From observations by Beranek[4] the modulus and argument of $Z/\rho c$ are 4.331 and $-36.55°$, respectively. Hence y

[1] C. T. Molloy and E. Honigman, J. Acous. Soc. Am. 16, 267 (1945).
[2] P. M. Morse, J. Acous. Soc. Am. 11, 205 (1939).
[3] *Table of the Bessel functions $J_0(z)$ and $J_1(z)$ for Complex Arguments* (Columbia University Press, New York, 1943).
[4] L. Beranek, J. Acous. Soc. Am. 12, 14 (1940).

$=-.2392+.3226i$, and $D=3.11$ db/ft. The method of Molloy and Honigman gives 29.6.

By expanding y about the higher roots of the Bessel function, J_1, one can derive an approximate formula for the attenuation of the higher modes of vibration:

$$D=.0154\frac{\nu}{\eta}r. \tag{10}$$

Here r is the root of $J_1(r)=0$ that is of the same order as the mode of vibration; thus, for the second mode, $r=3.83$. Formula (10) is accurate to within 5 percent for the range of practice indicated by the above examples.

The author takes pleasure in thanking Mr. Charles T. Molloy for helpful information relative to the problem.

The Conical Sound Source

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An asymptotic expansion has been derived from a formula given by W. N. Brown, which allows the plotting of directional and response curves for a vibrating cone in an infinite baffle. The results are compared with those pertaining to a flat disk of same radius.

IN a paper published some years ago W. N. Brown[1] calculated the acoustic pressure due to a rigid cone,[2] axially vibrating in an infinite baffle. He obtained, at large distance, and within the solid angle of cone, the following expression:

$$p = j\frac{\omega\rho_0 \sin\alpha}{r} U e^{-j(\beta r-\omega t)} \int_0^a e^{j\beta\cdot s\cdot\cos\vartheta\cos\alpha} T_0(\beta\cdot s\cdot\sin\vartheta\sin\alpha) s\cdot ds, \qquad (1)$$

where: $p = Pe^{j\omega t}$ = sound pressure at X (Fig. 1), $\omega = 2\pi f$, ρ_0 = density of air, $u = Ue^{j\omega t}$ = axial velocity of cone, $\beta = 2\pi f/c$ = phase constant, c = sound velocity, and f = frequency.

Equation (1) differs from the well-known one pertaining to a flat disk, the integrand being multiplied by $e^{j\beta s\cos\vartheta\cos\alpha}$.

The above integral does not seem to have been evaluated; some numerical values have been calculated by Simpson's rule, or with a mechanical integraph by Brown.

In this paper an asymptotic expansion is derived that has an interesting physical meaning, and simplifies the numerical computations.

This expansion enables one to plot directional and response curve of a universal type for a cone, with little more difficulty than for a flat disk.

Taking for brevity: $b = \beta\cos\alpha\cos\vartheta$; $g = \beta\sin\alpha\sin\vartheta$ and expanding the exponential in power

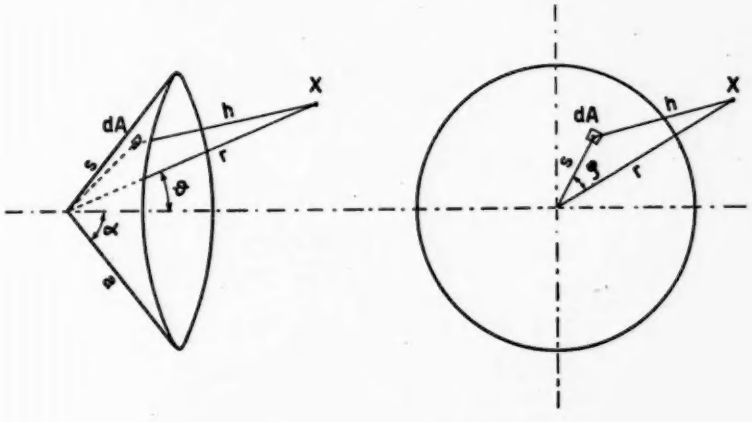

FIG. 1. Geometrical parameters of cone.

[1] W. N. Brown, "Theory of Conical Sound Radiators," J. Acous. Soc. Am. **13**, 20 (1941). See also R. W. Carlisle, "Conditions for Wide Angle Radiation from Conical Sound Radiators," J. Acous. Soc. Am. **15**, 44 (1943).

[2] The value of p is not exact because in deriving (1) it was assumed that the baffle was plane everywhere. In the paper quoted, the sign of the exponential was taken $e^{-j\omega t}$ instead of $e^{+j\omega t}$. It must be remembered that:

$$\int_0^{2\pi} e^{jz\cos\varphi} d\varphi = \int_0^{2\pi} e^{-jz\cos\varphi} d\varphi = 2\pi T_0(z).$$

See for instance N. W. McLachlan, *Bessel Functions for Engineers* (Clarendon Press, Oxford, 1934), p. 157, n. 10.

series, the following expression of integral (1) may be derived:

$$\int_0^a e^{jbs}T_0(gs)s\cdot ds=\int_0^a\left[1+j\frac{bs}{1!}-\frac{b^2s^2}{2!}-\cdots\right]T_0(gs)\cdot s\cdot ds=a^2\sum_0^\infty{}_n\frac{(jba)^n}{n!}G_n(ga), \tag{2}$$

where:

$$G_n(z)=\frac{1}{z^{n+2}}\int_0^z z^{n+1}T_0(z)dz. \tag{3}$$

The integral (2) is given by a series, whose coefficients $G_n(ga)$ are expressed by (3). The G_n can be easily evaluated using the following formulae:

$$\int_0^z z^nT_0(z)dz=z^nT_1(z)-(n-1)z^{n-1}T_2(z)+\cdots+[(n-1)(n-3)\cdots 2]z^{\frac{1}{2}(n+1)}T_{\frac{1}{2}n+1}(z), \tag{4}$$

(for n odd)

$$\int_0^z z^nT_0(z)dz=z^nT_1(z)-(n-1)z^{n-1}T_2(z)+\cdots+[(n-1)(n-3)\cdots 1]\int_0^z z^{\frac{1}{2}n}T_{\frac{1}{2}n}(z)dz, \tag{5}$$

(for n even)

$$\int_0^z z^{\frac{1}{2}n}T_{\frac{1}{2}n}(z)dz=z^{\frac{1}{2}n}T_{\frac{1}{2}n+1}(z)+z^{\frac{1}{2}n-1}T_{\frac{1}{2}n+2}(z)+\cdots+[1\cdot 3\cdot 5\cdots(n-1)]\int_0^z T_n(z)dz, \tag{6}$$

$$\int_0^z T_n(z)dz=2\sum_0^\infty{}_h\,T_{n+2h+1}(z). \tag{7}$$

The Bessel series in (7) converges quickly, and is a very convenient one for numerical computations. For the first G_n one obtains:

$$\left.\begin{aligned}
G_0(z)&=\frac{T_1(z)}{z},\\
G_1(z)&=\frac{T_1(z)}{z}-\frac{T_2(z)}{z^2}-\frac{1}{z^3}\int_0^z T_2(z)dz,\\
G_2(z)&=\frac{T_1(z)}{z}-2\frac{T_2(z)}{z^2},\\
G_3(z)&=\frac{T_1(z)}{z}-3\frac{T_2(z)}{z^2}+3\frac{T_3(z)}{z^3}+3\frac{T_4(z)}{z^4}+\frac{9}{z^5}\int_0^z T_4(z)dz,\\
G_4(z)&=\frac{T_1(z)}{z}-4\frac{T_2(z)}{z^2}+8\frac{T_3(z)}{z^3},\\
G_5(z)&=\frac{T_1(z)}{z}-5\frac{T_2(z)}{z^2}+15\frac{T_3(z)}{z^3}+15\frac{T_4(z)}{z^4}+15\frac{T_5(z)}{z^5}+15\frac{T_6(z)}{z^6}+\frac{2z5}{z^7}\int_0^z T_6(z)dz,\\
G_6(z)&=\frac{T_1(z)}{z}-6\frac{T_2(z)}{z^2}+24\frac{T_3(z)}{z^3}-48\frac{T_4(z)}{z^4}.
\end{aligned}\right\} \tag{8}$$

TABLE I.

z	$G_0(z)$	$G_1(z)$	$G_2(z)$	$G_3(z)$	$G_4(z)$	$G_5(z)$	$G_6(z)$
0	0,500	0,333	0,250	0,200	0,167	0,142	0,125
1	0,440	0,305	0,210	0,163	0,137	0,116	0,100
2	0,290	0,185	0,114	0,082	0,064	0,0525	0,044
3	0,110	0,043	0,002	−0,011	−0,014	−0,015	−0,015
4	−0,015	−0,047	−0,0606	−0,069	−0,0528	−0,054	−0,043
5	−0,070	−0,093	−0,074	−0,058	−0,0540	−0,050	−0,041

Note: for American usage the commas in this table should be periods.

If $n>6$ and for $0<z<5$, G_n is approximately expressed by:

$$G_n(z)\approx\frac{1}{n+2}T_0\left(z\frac{n+2}{n+3}\right). \tag{9}$$

Some numerical values of $G_n(z)$ are given in Table I. It is easily seen that:

$$\lim_{z\to 0} G_n(z)=1/n+2. \tag{10}$$

Substituting series (2) in (1), one gets:

$$p=j\frac{\omega\rho_0 a^2\sin\alpha}{r}Ue^{-j(\beta r-\omega t)}\sum_0^\infty{}_n\frac{(j\beta a\cos\vartheta\cos\alpha)^n}{n!}G_n(\beta a\sin\vartheta\sin\alpha). \tag{11}$$

As said before, development (1) has an interesting physical meaning. The first term:

$$j\frac{\omega\rho_0 a^2\sin\alpha}{r}Ue^{-j(\beta r-\omega t)}.\frac{T_1(\beta a\sin\vartheta\sin\alpha)}{\beta a\sin\vartheta\sin\alpha}$$

gives the pressure due to a flat disk of the same radius as the base of cone. The following terms give corrections of higher orders; of course they vanish with frequency and height of cone. It is particularly convenient that the number of terms needed becomes smaller as the cone approaches to a disk.

On the axis the pressure can be obtained taking: $\vartheta=0$ and evaluating (1), or otherwise from series (11). In both ways one gets:

$$p_{\vartheta=0}=j\frac{\omega\rho_0 a^2\sin\alpha}{r}Ue^{-j(\beta r-b t)}\frac{e^{-j\beta a\cos\alpha}[1-j\beta a\cos\alpha]-1}{\beta^2a^2\cos^2\alpha}$$

$$=j\frac{\omega\rho_0 a^2\sin\alpha}{r}Ue^{-j(\beta r-\omega t)}\left[1+j\frac{1}{3\cdot 1!}ba-\frac{1}{4\cdot 2!}b^2a^2-\cdots\right]. \tag{12}$$

Substituting the sines and cosines for the exponential, the r.m.s. value of pressure is proportional to:

$$|p|_{\vartheta=0}\propto\frac{[(\cos x+x\sin x-1)^2+(\sin x-x\cos x)^2]^{\frac{1}{2}}}{x^2}, \tag{13}$$

where: $x=\beta a\cos\alpha$.

From Fig. 2 it appears that the pressure on the axis of a mass-controlled cone decreases with increasing frequency, while it does not vary for a disk.

When apical angle and βa are given, expansion (11) allows the plotting of directional curves of universal type by means of values of G_n given in Table I. The characteristics for a disk and two cones, of different apical angles but with the same radius of base are portrayed in Fig. 3 for comparison purposes.

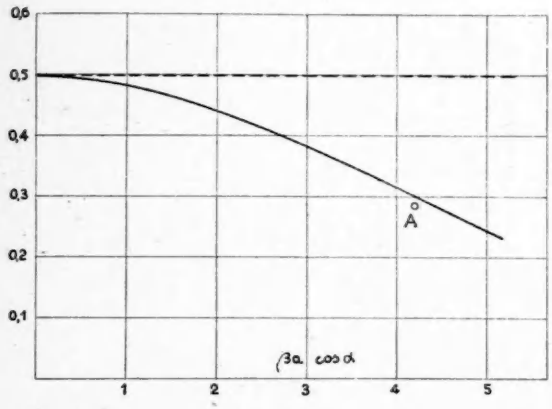

FIG. 2. Pressure on the axis of a mass-controlled cone (solid curve) and of a flat disk (dotted curve). A: point calculated by Brown.

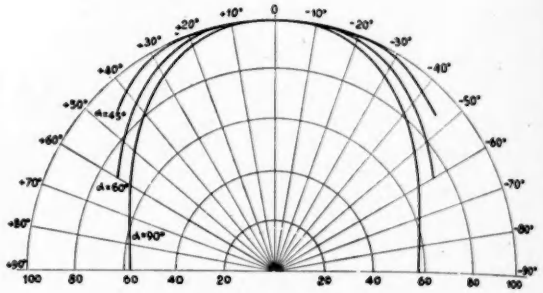

FIG. 3. Directional curves of a flat disk ($\alpha=90°$) and of two cones ($\alpha=60°$ and $\alpha=45°$) of same basis.

The greater flatness of cone curves with respect to a disk can perhaps be noticed in laboratory measurements, but is devoid of interest in technical work. When $\beta a<2$ the agreement between cone and disk is better; it becomes worse when $\beta a>2$, the last case however is not of interest, because at such frequencies a cone does not vibrate as a whole, but usually breaks up in modes with several nodal lines, the sound radiation being then quite different.

CONCLUSION

The pressure radiated by a mass-controlled cone decreases on the axis as frequency increases, instead of keeping constant, as it does with a disk.

The directional curves are like those of a disk of the same radius, but a little flattened.

The above results give a mathematical proof that, in most technical work, a conical radiator can be approximated by a flat disk of equal radius as is usually done in an empirical way.

The writer takes this opportunity to thank Professor A. Giacomini, Director of the National Electroacoustical Institute, who offered valuable suggestions and encouragement in the preparation of the paper.

Measurement of Supersonic Absorption in Water by the Balance Method with Mechanical Integration*

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(Received July 21, 1945)

INTRODUCTION

THE intensity absorption coefficient for sound propagation in a fluid is usually defined as 2α, where

$$I = I_0 e^{-2\alpha x} \tag{1}$$

is the acoustic intensity in a plane wave at distance x from some arbitrarily chosen indicial plane at which the intensity is I_0. In the past decade there have been numerous measurements of 2α for water in the frequency range from 1 to 80 megacycles.[1–7] These have yielded a somewhat disconcerting diversity of values, though the one striking feature of them all is that 2α for all frequencies comes out much higher than that predicted by the viscosity theory of Stokes,[8] according to which

$$2\alpha = 16\pi^2\mu\nu^2/3\rho_0 c^3, \tag{2}$$

where μ = coefficient of viscosity, ν = frequency, ρ_0 = mean density, and c = velocity of sound in the fluid. While the measurements in general indicate an increase of 2α with ν, the square law has so far received no definite confirmation over an extensive range of frequencies except in the work of Fox and Rock.[7] A repetition of the measurement of the absorption coefficient of water by an alternative method therefore has appeared desirable.

The experimental difficulties in the measurement of 2α are considerable and numerous sources of error exist, among them: (1) the sound divergence from the source with the accompanying diffraction pattern, (2) multiple reflections from the walls of the vessel in which the radiation takes place and from the detecting mechanism, (3) cavitation and air bubbles accompanying high intensity, (4) hydrodynamic flow, and (5) surface tension. It is the aim of the present paper to describe a method which it is believed is free from many of the above difficulties and minimizes the consequences of all of them.

The method herein described is a variant of the well-known balance method in which the upward acoustic radiation pressure exerted on an object suspended vertically in the sound beam is weighed directly by a sensitive balance, and thus provides a quantity directly proportional to the average intensity of the acoustic radiation over the surface of the detector.

APPARATUS AND METHOD

(a) Source

The supersonic radiation was provided by four one-inch square X-cut quartz crystals with fundamental frequencies 1.488, 2.473, 4.431, and 5.078 megacycles respectively. Tightly adherent electrodes were secured by first evaporating silver coatings on the surfaces of each crystal and electroplating the silver with copper. One side of each crystal was plated in its entirety whereas on the reverse side the plating was confined to a circular area 13/16 inch in diameter. Each crystal was then cemented to a circular brass plate 11.5 cm in diameter with a center hole 15/16 inch in diameter over which the circular area was placed and carefully centered. The brass plate together with the totally plated surface was grounded, while the circular area was attached to the high potential lead. The brass plate was then used as the bottom of the water tank in which the radiation was studied. Figure 1 indicates the method of mounting the crystal and Fig. 2 shows a sketch of the whole assembly.

To drive the quartz crystals two radio-frequency oscillators were employed, the first

* Part of a thesis submitted to the Graduate School of Brown University for the degree of Doctor of Philosophy.
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[1] M. P. Biquard, Thèses Université de Paris (1935); Ann. de Physique **6**, 195 (1936).
[2] C. Sörensen, Ann. d. Physik **26**, 120 (1936).
[3] R. Bär, Helv. Phys. Acta **10**, 332 (1937).
[4] H. Grobe, Physik. Zeits. **39**, 333 (1938).
[5] G. K. Hartmann and A. B. Focke, Phys. Rev. **57**, 221 (1940).
[6] G. W. Willard, Phys. Rev. **57**, 1057A (1940).
[7] F. E. Fox and G. D. Rock, J. Acous. Soc. Am. **12**, 505 (1941).
[8] G. G. Stokes, Trans. Camb. Phil. Soc. **8**, 287 (1845).

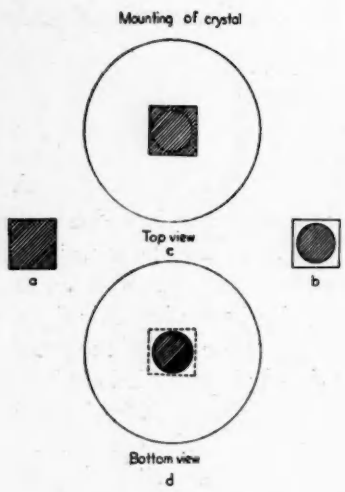

FIG. 1.

with a frequency range of 1 to 28 megacycles and the second ranging from 20 to 150 megacycles. Harmonics of the crystals as high as the thirteenth were employed for the upper frequencies. Measurements were made at a variety of frequencies in the interval from approximately 10 to 58 megacycles.

(b) Detector

After considerable experimentation with suspended metal cones of various sizes and vertex angles, it was finally decided to use as detector a plane surface 1.5 cm square (about 10 grams in mass) hung from one pan of the balance by a bifilar suspension which served to eliminate rotational motion of the detector. The surface of the detector facing the radiation was covered with fine sand attached by means of insoluble Duco cement. The sand particles were of the order of 1/100 cm in diameter and acted to replace regular reflection of the sound by non-uniform scattering, thus avoiding the setting-up of standing waves. Even at the highest frequencies used, the regular reflection was negligible.

To provide for horizontal motion of the detector, arrangements were made to slide the balance along tracks, with a total possible motion of 15 cm and 20 cm respectively in perpendicular directions. This is indicated in Fig. 3, which shows the whole assembly as it was actually used. Since the tank itself was provided with a means of vertical motion it was possible for the detector to reach any point in the radiation. When the detector was placed at any given distance from the source to measure the radiation pressure, because of its small size it intercepted only a fraction of the entire sound beam. The total area of the diffraction zone was divided into square sections, each of area equal to that of the detector. The radiation pressure at each one of these square sections was measured by suspending the detector there and noting the difference in the balance reading in milligrams when the sound was turned on and off. This was done for each square section in turn out to the edges of the beam and the integrated radiation pressure, which might properly be called the total radiation force, was taken as the sum of all these results. With this method of integration the balance method of "weighing" sound may be expected to yield more accurate results than single weighings at any one point in the beam. No matter how divergent the beam, integration assures that no fraction of the radiation is overlooked. Another advantage is the reduction in mass and size of the detector and the consequent increase in the sensitivity of the balance.

A chainomatic balance was employed with a sensitivity of 5-scale divisions per milligram for the detector used. Weights were estimated to 0.05 milligram. Since the detector was attached to the balance by a bifilar suspension the edges of the detector could readily be made parallel to the horizontal motions. Thus the whole beam could be covered exactly without the presence

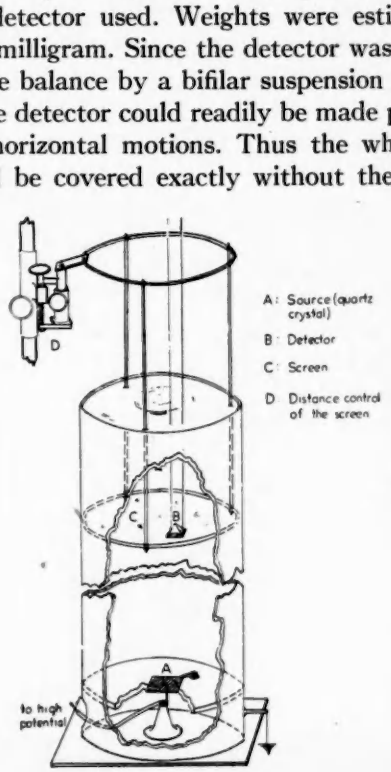

FIG. 2.

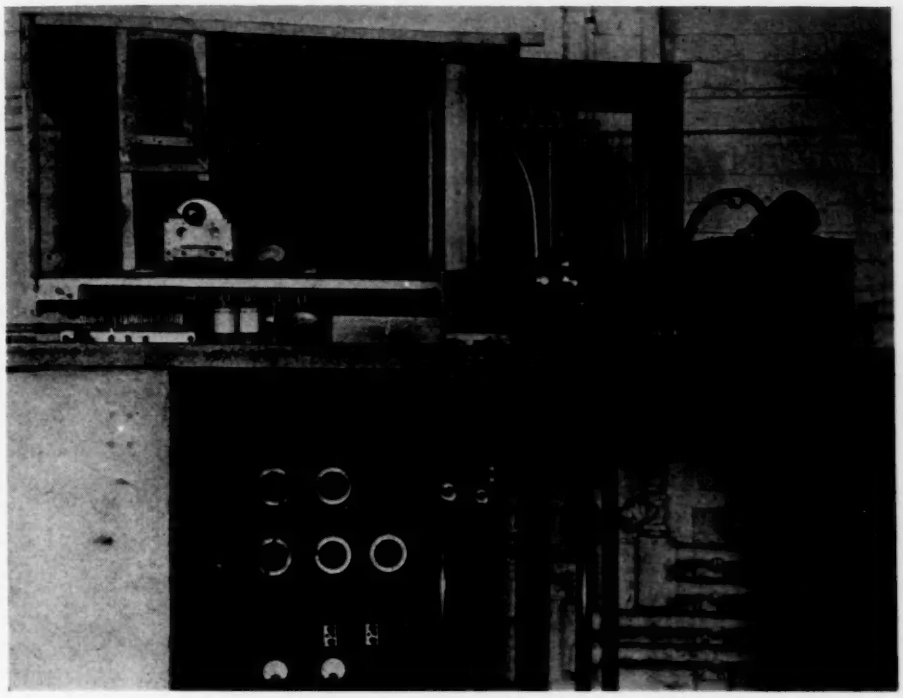

FIG. 3.

of gaps or overlapping. Horizontal displacements of the detector could be estimated to 0.1 mm.

To decrease the adverse effect of surface tension on the validity of the weighing, the wires used for the detector suspension were very fine, with diameter 0.007 cm. The use of oil to lower the surface tension was abandoned because of the resulting contamination of the water. The best way to detect low intensity radiation was to put a few tenths of a milligram on the right-hand pan of the balance when the equilibrium had already been achieved. A quasi-equilibrium would then be maintained by the surface tension. An exceedingly small amount of radiation proved to be capable of destroying this equilibrium.

To avoid cavitation, already mentioned as a source of error in sound absorption measurements in liquids, it was desirable to keep the acoustic intensity below 0.03 watt/cm^2. This was achieved by adjusting the current through the crystal to give a total weight difference between sound off and on of 6 mg at a distance of 6 mm from the source.

(c) Tank

The tank used in the investigation was a brass cylinder 11 cm in diameter, consisting of three demountable sections and a base with a brass disk serving as the crystal holder. With all three sections in place the height of the tank was 32 cm. Though too small for low frequencies it was satisfactory for the frequency region used in this research. To prevent multiple reflections from the walls sand similar in nature to that used on the bottom of the detector was attached to the interior. Over the frequency range used the tank was sufficiently deep to attenuate any radiation reflected from the air-water surface and returning toward the source. It is estimated that at 10.4 megacycles, the lowest frequency used, less than 4 percent of the original intensity would be left after one round trip up and down the tank.

As is indicated in Fig. 3, the tank was mounted on a brass bar which was movable along two vertical copper tubes by a ten-inch precision screw. A slow and uniform vertical motion was obtainable thereby and vertical displacements could be measured with an accuracy of 0.01 cm.

To cut down the effect of hydrodynamic flow a Cellophane screen was stretched on a light but rigid brass frame which could be moved vertically inside the tank, as shown in Fig. 2.

The water investigated was ordinary tap water which had been left open to the air for at least a week to reach equilibrium with respect to dissolved air before it was carefully siphoned into the tank. Small changes in temperature were tolerated but the range was well within 5°C of normal room temperature.

RESULTS

The absorption coefficient 2α was measured for ten frequencies distributed over the range from 10.42 to 57.60 megacycles, respectively (cf. Table I). Each quoted value of 2α is based on measurements of the integrated radiation pressure for at least four different distances from the source, the accepted value being taken as the average determined by using all possible combinations among these four.

The following sample measurement for $\nu = 12.36$ megacycles will serve as an illustration. Each square array gives a mapping of the cross section of the sound beam at the stated distance D from the source. I denotes the integrated radiation pressure in milligrams.

1. $D = 18.0$ cm, $I = 3.90$ mg

0	0	0	0	0
0	.10	.15	.10	0
0	.15	2.90	.15	0
0	.10	.15	.10	0
0	0	0	0	0

2. $D = 17.0$ cm, $I = 4.20$ mg

0	0	0	0	0
0	.10	.15	.10	0
0	.15	3.20	.15	0
0	.10	.15	.10	0
0	0	0	0	0

3. $D = 16.0$ cm, $I = 4.50$ mg

0	0	0	0	0
0	.10	.15	.10	0
0	.15	3.50	.15	0
0	.10	.15	.10	0
0	0	0	0	0

4. $D = 15.0$ cm, $I = 4.80$ mg

0	0	0	0	0
0	.10	.15	.10	0
0	.15	3.80	.15	0
0	.10	.15	.10	0
0	0	0	0	0

5. $D = 14.0$ cm, $I = 5.15$ mg

0	0	0	0	0
0	.10	.15	.10	0
0	.20	3.90	.20	0
0	.15	.20	.15	0
0	0	0	0	0

6. $D = 13.0$ cm, $I = 5.55$ mg

0	0	0	0	0
0	.15	.20	.10	0
0	.20	4.20	.20	0
0	.15	.20	.15	0
0	0	0	0	0

7. $D = 12.0$ cm, $I = 5.95$ mg

0	0	0	0	0
0	.15	.20	.15	0
0	.20	4.55	.20	0
0	.15	.20	.15	0
0	0	0	0	0

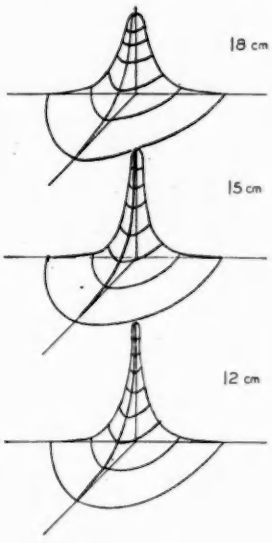

FIG. 4. Energy distribution in sound beam.

It will be noted that the pressure distribution is not always uniform over the beam. Figure 4 is a sketch of the three-dimensional energy distribution in the sound beam at three separate distances from the source for the frequency in the sample measurement here under consideration.

Table I lists the final values of 2α (in cm^{-1}) for the ten frequencies studied, as well as the value of $2\alpha\nu^{-2}\times10^{17}$ (in cm^{-1} $sec.^2$). For convenience the absorption coefficient is also tabulated in db/cm. The average value of $2\alpha\nu^{-2}\times10^{17}$ is 45.4 cm^{-1} $sec.^2$.

Figure 5 presents a plot of $2\alpha\nu^{-2}\times10^{17}$ for the present work as well as that of other investigators. The present values all lie close and within the limit of experimental error to the horizontal line corresponding to the average value 45.4 cm^{-1} $sec.^2$ for $2\alpha\nu^{-2}\times10^{17}$. It will be noted that

TABLE I. Values of $2\alpha\nu^{-2}\times10^{17}$ at different frequencies.

ν	2α	db/cm	$2\alpha\nu^{-2}\times10^{17}$
10.42 megacycles	0.0479	0.208	44.1 cm^{-1} sec.
12.36	0.0702	0.305	46.0
13.39	0.0802	0.348	44.7
16.37	0.118	0.513	44.1
17.32	0.139	0.604	46.3
19.34	0.170	0.738	45.4
22.16	0.220	0.956	44.8
25.39	0.303	1.32	46.9
39.85	0.722	3.14	45.1
57.60	1.53	6.64	46.1

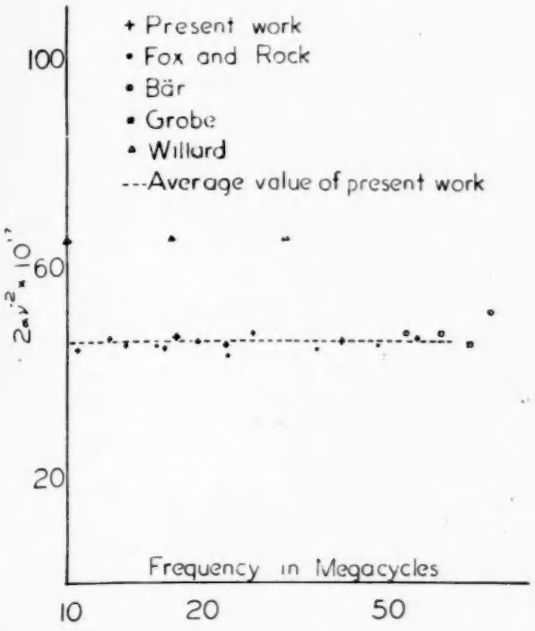

FIG. 5.

there is good general agreement between the present values and those obtained by Fox and Rock.[7] It should be mentioned that the latter obtained two values at frequencies slightly below 10 megacycles, which are therefore not included in the graph; these also are in general agreement with the average horizontal line.

The conclusion of the investigation is that over the frequency range studied the acoustic absorption coefficient of water varies directly as the square of the frequency. No indication of any absorption band or a drop of $2\alpha\nu^{-2}\times10^{17}$ with increasing frequency appears in these results.

THEORETICAL CONSIDERATIONS

The present investigation yields results in qualitative agreement with the classical absorption theory of Stokes, though the value of $2\alpha\nu^{-2}$ is more than $2\frac{1}{2}$ times that predicted by the Stokes theory and given in Eq. (2). Various attempts have been made to account for a discrepancy of this size, notably by Lucas,[9] Kneser,[10] Richards,[11] and Tisza.[12] It is felt that considerable plausibility attaches to the view of Lucas and Tisza that in the derivation of Stokes' formula the quantity

$$2\mu+3\lambda,$$

where μ is the ordinary shearing viscosity coefficient and λ is the so-called "compression" coefficient, should not be placed equal to zero. According to this the revised Stokes' formula should become

$$\frac{2\alpha}{\nu^2}=\frac{4\pi^2(\lambda+2\mu)}{\rho_0 c^3}. \tag{3}$$

If the viscosity of water at 20°C is taken as $\mu=10^{-2}$ dyne sec./cm^2, the use of the experimental value 45.4×10^{-17} for $2\alpha/\nu^2$ leads to the following approximate relation between λ and μ

$$\lambda=1.56\mu. \tag{4}$$

It is perhaps of interest to observe that in the case of solids the two extreme values of the corresponding elastic moduli are $\lambda'=\mu'$ and $\lambda'=2\mu'$.

The viewpoint of Lucas that the sub-microscopic structure of liquids probably has some connection with the observed acoustic absorption should receive further theoretical and experimental study. In this connection it would be of interest to determine the dependence of the absorption coefficient on temperature over as wide a range of values as possible.

The author is pleased to acknowledge his indebtedness to Professor R. B. Lindsay for his suggestion of the research topic and his constant encouragement. His sincere thanks are due particularly to Professor L. W. Labaw for invaluable assistance in suggesting and criticizing the method of measurement.

[9] R. Lucas, Comptes rendus **201**, 1172 (1935), **203**, 459 (1936), **203**, 611 (1936), **206**, 658 (1938); J. de phys. et rad. **8**, 41 (1937).
[10] H. O. Kneser, Ann. d. Physik **32**, 277 (1938).
[11] W. T. Richards, Rev. Mod. Phys. **11**, 36 (1939).
[12] L. Tisza, Phys. Rev. **61**, 531 (1942).

"Higher Fidelity" in Sound Transmission and Reproduction

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(Received April, 1945)

A CONSIDERATION of the term "higher fidelity" implies an improvement in the standard of service or performance now being rendered in sound transmission and reproduction. The system requirements are in the main largely the same whether we are concerned with recording and reproduction; with radio transmission and reception, or with a similar service. Any improvements made must of necessity include a study of the related factors to see what is involved in these further steps toward realism.

The vast majority of sound systems in use today and those contemplated for the immediate future will be single channel or monaural systems. The use of a single channel imposes an immediate limitation, that is, the lack of perspective or spatial orientation. A single channel may be completely free from all the various limitations now known and yet lack complete realism, because of this absence of the ability to "locate" aurally the sources of sound. It is not the purpose of this paper to argue the relative merits of the binaural, two-channel, or "stereophonic" sound systems except that such systems do approach realism (other factors being comparable) far better than the single channel system with which most people are familiar.

The term "high fidelity" seems to connote generally an extension in frequency range; that is, an extension in the upper limit of from say 5000 cycles to 8000 cycles or higher. The total frequency range over which the average human ear, when young, responds is about 20 to 17,000 cycles. This frequency range is generally considered adequate to include all those sounds which we wish to hear. The reproduction of such a range does however introduce, in addition to technical problems, economic problems as in the case of radio broadcasting. Most of the attention in recent years has been directed at the higher frequencies rather than at a balance between the low frequencies and the high frequencies. The proper balance between the upper and lower frequency limits is of major importance as contrasted to a selection of a suitable upper frequency limit for a particular purpose or service. Our experience has indicated that the product of the lower and upper frequency limits should equal approximately 500,000. The desirability of such a balance may be shown by considering one system whose range is 200 to 10,000 cycles and one whose range is 60 to 8000 cycles. The second would be preferred yet the frequency range of the first is appreciably greater. Figure 1 shows "preferred lower and upper frequency range," and it will be seen that the various types of the "average" home radio receiver approach these requirements surprisingly well.

The vast majority of people have been listening for many years to a restricted frequency response on sound motion pictures, radio receivers or phonographs. This type of listening may have become their reference standard of quality because, except in the case of the spoken word, there may be no convenient way for them to compare the original with the reproduced—that

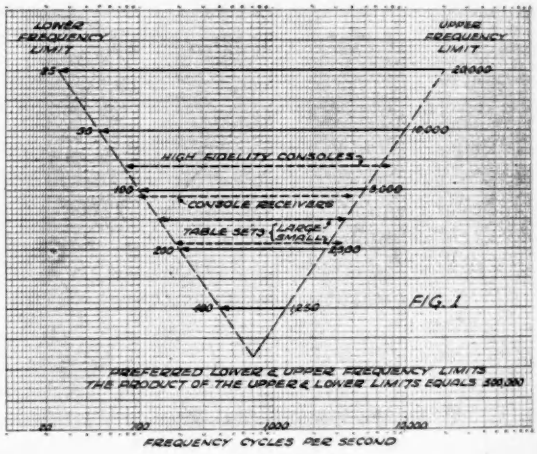

FIG. 1.

is, comparatively few have listened directly to a symphony orchestra to appreciate how it sounds. It is not to be expected that the expansion of the frequency range will be accepted readily at once by many because of this conditioning. In many

instances, the expansion of the range will contribute comparatively little—particularly as in the case of dialogue or speech. Further, many "music lovers" are more concerned with the technique of performance than with realism. As the lower frequency limit is extended downward, at the point of program origin, sounds previously inaudible through the system will become apparent. As the higher frequency limit is extended, distortion products previously unnoticed may become quite audible and disturbing together with noises from the equipment or studio. These noises may be tube hiss, thermal agitation, from the air-conditioning systems or resin and valve squeaks, and the like. These problems are not insoluble by proper engineering and microphone techniques, but they increase the difficulties attendant to the design and operation of a sound system.

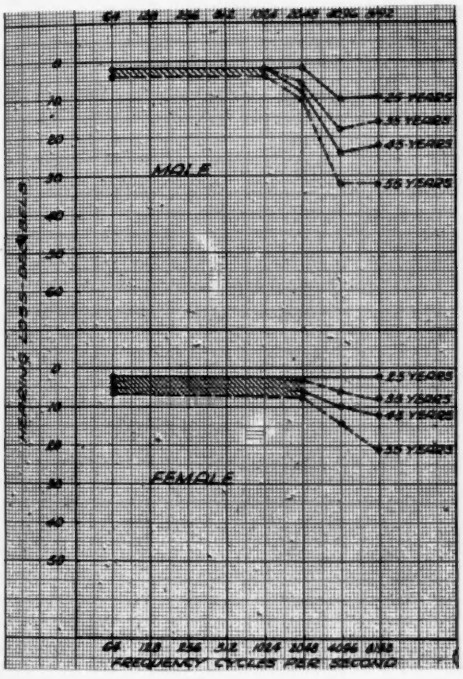

FIG. 2. Hearing loss *vs.* age (U. S. Public Health Service Bulletin, No. 5, 1938).

Sound isolation systems employed in studio construction in general become increasingly less effective as the frequency is lowered and sound control becomes more difficult at the lower frequencies.

The major portion of the energy from most sound sources is below 10,000 or 12,000 cycles and that above contains mostly noises such as handclapping, paper rustling, jangling of keys,

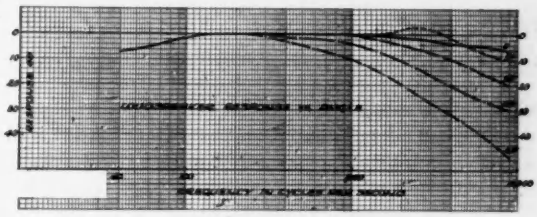

FIG. 3.

etc., or noises incidental to the production of the desired sounds.

The acoustical conditions surrounding the performers and the listeners also become more difficult to control as the range is extended. Information is available generally on the absorption properties of acoustical materials only from 128 to 4096 cycles. Sound control can be exercised over a range from 60 to 8000 cycles, by those who have access to information and experience with some acoustical materials over this range. At the higher frequencies of 4000 cycles and above, the absorption of air itself becomes a factor. At a relative humidity of 50 percent the reverberation time at 10,000 cycles, regardless of the volume of the room, is limited to about 1.5 seconds even though the walls, ceiling, and floor are perfectly reflective; at 12,000 cycles the limit is about 1.2 seconds; and at 15,000 cycles, about 0.9 second. These conditions have, of course, existed for years in concert halls and rooms of all kinds but our present practice is to design rooms for program origination to certain specified criteria. The magnitude of the sound absorption in the air itself at the higher frequencies and the absence of performance data on materials at extremes of the frequency range impose a severe limitation on our ability to control acoustical conditions to the extent desired.

The volume range of most sound systems is limited, the lower intensities by noise of one sort or another and at the upper intensities by the load handling capacity of the system without noticeable distortion. It is necessary in almost

all sound systems to employ manual volume control, or semi-automatic volume control, or both to adjust the dynamic range of the source of sound to that which the system can handle. It is usual for this range to be reproduced without

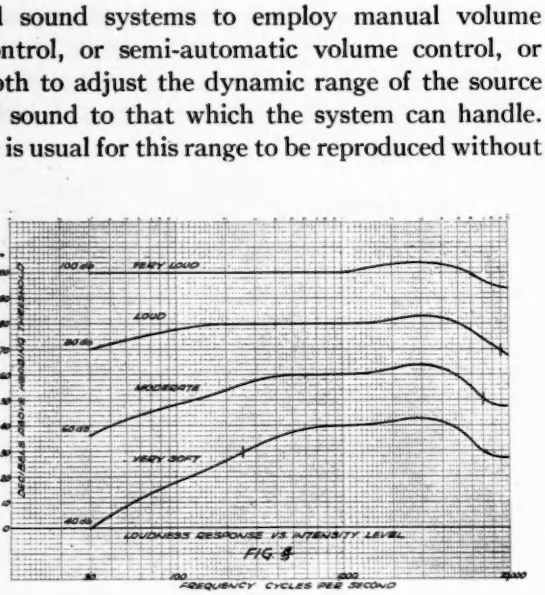

FIG. 4.

compensation for the compression which has been accomplished—that is, the dynamic range is not restored by expansion on the reproducing end of the system. In the case of radio reception in the city and suburbs, it would not be possible to reproduce the original range without elaborate precautions as to sound isolation or the careful location of the home adjacent to neighbors with impaired hearing. The dynamic range of usual program sources may be 70 db or greater. The noise level in the average home is about 35 db and consequently sound levels of 90 db and higher would be necessary for full reproduction (assuming the program material may be allowed to drop 10 db or so into the noise without substantial loss because of masking).

There is some evidence to indicate that while people do prefer a high signal-to-noise ratio there is a similar preference or tolerance, perhaps unwittingly, for a restricted dynamic range provided the restriction is not excessive or accomplished in a noticeable manner. Frequently, these two conditions are considered as one whereas in many cases they are different and should be so treated.

Another factor is the characteristics of the human ear; it is generally known that the acuity to higher frequency sounds diminishes with an increase in age. See Fig. 2. This loss of hearing, whether caused by natural processes or by external influences, is difficult to evaluate properly in importance. Hearing loss measurements were made of a number of engineers, program producers, and musicians at NBC some years ago to attempt to correlate hearing loss with ability to judge program quality. In a few cases where hearing was impaired to the extent of 40 db at frequencies of 4000 cycles and higher, the particular individuals were actually among the most competent of those concerned with exercising judgment of program quality. This would appear contradictory except that because of association with many others in the judgment of quality it would be unlikely that any abnormal judgments would persist for too long a time. In several of these cases, no difference was observed when the frequency range of a program was restricted somewhat without their knowledge.

The angular response of conventional loudspeakers discriminates against the higher frequencies with an increase in both the frequency and the angle subtended to the axis of the speaker. A typical curve is shown in Fig. 3.

The balance between low frequencies and the high frequencies is determined by the intensity of reproduction and the loudness intensity response of the ear. See Fig. 4. If we combine Fig. 3 and Fig. 4, we have Fig. 5 which indicates in a general way the over-all response at a reasonable position of listening.

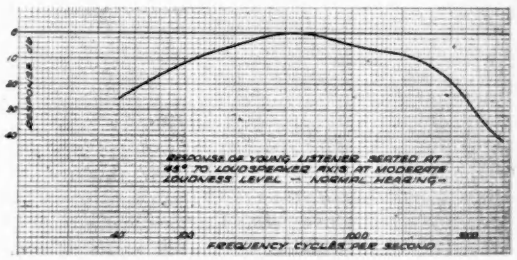

FIG. 5.

The problem of improving the approach to true realism in sound systems, as in similar lines of endeavor, becomes increasingly difficult as the criterion is approached. Unfortunately, it is neither economical nor practical to provide the

utmost and allow the user to make his selection as to his preference of the kind of fidelity he wishes.

It is evident that our knowledge at present does not permit us to solve in an entirely satisfactory manner some of the technical problems and other problems which are related, but outside the technical field. It is our function in the field of engineering to provide the best possible service far in advance of the public requirements and where desired factors and limitations are in conflict to evaluate intelligently the relative importance of the particular factor involved and its relation to the service rendered.

Aero-Otitis Media in Submarine Personnel

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(Received June 23, 1945)

THE most common injury seen in persons exposed to rapid changes in barometric pressure is the syndrome known as aero-otitis media. In the progress of the war with the increase in aviation, submarine activity, and diving, this injury has become a problem of general interest. In addition it is a recognized occupational injury. Armstrong[1] was one of the first to describe this injury and labelled it aero-otitis media. McGibbon used the term aviation pressure deafness, and the English and Germans refer to acute otitic barotrauma. In this country it is generally called aero-otitis media.

Aero-otitis media is the injury occurring from failure to equalize pressure within the middle ear. The equalization occurs normally through the eustachian tube; but if blocked, stenosed, or if it fails to open sufficiently to allow for equalization of pressure, aero-otitis media results. Improper ventilation through the eustachian tube may be due to pathological conditions, such as tissue masses or swollen lining membrane, or to inability or failure to voluntarily open the tube.

The eustachian tube is a slit-like potential tube connecting the nasopharynx with the middle ear. It consists of a bony portion and a fibro-cartilaginous portion. The bony portion remains rigid but the yielding wall of the fibro-cartilaginous portion is closed and is the portion opened voluntarily in the equalization of pressure. This cartilaginous portion is approximately 24 mm in length and opens into the nasopharynx. The mucous membrane of this part of the tube is thick and very vascular, contains many mucous glands, and is lined with columnar epithelium. Near the mouth of the tube is found a varying amount of lymphoid tissue, such as adenoids.

The function of the eustachian tube is to drain and ventilate the middle ear. The ciliary action and slit-like opening of the mouth of the tube favor discharge from the middle ear to the nasopharynx and oppose any reverse current. During swallowing, yawning, voluntary inflation, or similar action, the dilator muscles open the eustachian tube, allowing intake of air for any pressure equalization or of the middle ear if needed. This procedure is utilized by those working in changing pressure conditions. Failure to equalize pressure leads to discomfort and injury of the ears.

There have been many laboratory investigations of the physiology of the eustachian tube under varying degrees of pressure. It has been noted that the eustachian tube is forced open when the pressure in the middle ear is from 15 to 11.4 mm of mercury of pressure. The difference is due to the difference in density of air and its viscosity. The eustachian tube is forced open by the escaping air, and the pressure relieved. On the other hand, the pressure against the middle ear must be voluntarily relieved before the pressure about the tube reaches 80 to 90 mm of mercury, for at this time the edges of the tube are pressed closed and it is impossible for the dilator muscles to force it open. This is what Armstrong calls a "locked" tube. If this condition is not relieved by reducing the pressure to a level where the tube may be opened voluntarily, aero-otitis media results.

Two of the most frequent causes of eustachian blockage are hypertrophied lymphoid tissue about the eustachian orifice, and chronic infection of the nasopharynx. Other causes are: first—actual infection of the eustachian tube itself; second—acute colds (these have little effect if the eustachian tube is clear of lymphoid hyperplasia); third—polyps in the eustachian tube (this has been demonstrated by Fowler); and fourth—paralysis of pharyngeal muscles as well as mental state of the individual, whether asleep or unconscious. Malfunction of mandible leads to poor ventilation of the middle ear. This angle is under investigation at the present time by Kelly in New London.

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* Lieutenant (jg) (MC) U. S. Naval Reserve.
[1] H. G. Armstrong, *Aviation Medicine* (London, 1939).

The symptoms of aero-otitis depend on the severity and circumstances of the trauma. A positive pressure of only 3 to 5 mm of mercury within the middle ear is perceptible as a feeling of fullness. Pressures of 10 to 15 mm of mercury are outright annoying, and sounds are distant. Pressures of 15 to 30 mm of mercury cause tinnitus and some pain. Vertigo may occur. Usually at 15-mm mercury the eustachian tube opens, equalizing the pressure and relieving the symptoms.

In negative pressure within the middle ear, the symptoms are the same if not relieved by swallowing or opening of the tube. At 60 mm of mercury there is definite pain in the ear, radiating over the side of the head and parotid gland. Symptoms increase with increase in pressure. The ear drums usually rupture between 100 to 500 mm mercury. With rupture of the drum, the symptoms of increased pressure are relieved; even the hearing is very little affected. There may or may not be persistent pain in the ruptured ear. In our experience pain seldom persists more than a few moments. Many ears rupture with very little pain at all. (If these ruptured drums are left alone they heal in from one to four weeks. If treatment is attempted, a permanent perforation may result from induced infection.)

Objectively there is a great variation in the appearance of the drum and the middle ear in aero-otitis media. The drum may be either retracted or bulging. The amount of vascular engorgement may be only slight about the malleus and anterior and posterior folds, which we call a No. 1 ear; or it may be diffusely injected, which is designated as a No. 2 ear; or it may have minute hemorrhages about ruptured blood vessels in the drum, designated as No. 3 ears; or the whole middle ear may be filled with free blood and bubbles, which is designated as a No. 4 ear; or the drum may appear diffusely blue-black as one sees in cases of fracture of the base of the skull. It is the last-mentioned type of drum that is accompanied by a rather marked deafness and is designated as a No. 5 ear. The other types described above show very little hearing loss other than 5 to 10 db. (That, however, is a significant loss.)

The blood and fluid seen in these ears originates not only from the drum but appears to come from the lining mucous membrane of the middle ear as well. Campbell[2] in England described the pathological appearance of the mucosa in the ears of cats after the production of aero-otitis media. In these the vascular disturbances—vascular dilitation, oedema, hemorrhage, and effusion—are comparable to the effects of "cupping" on the skin.

Thompson, Howe, and Hughson,[3] 1934, demonstrated that variations in the pressure of the middle ear are not communicated to the inner ear fluids.

An ideal opportunity for the study of aero-otitis media is presented at the U. S. Submarine Base, New London, Connecticut. All candidates for Submarine School are subjected to 50 pounds pressure in a period of 5 to 15 minutes in a dry recompression chamber before being permitted to enter the water for submarine escape training. Over 3000 men were examined just prior to and immediately after emerging from pressure. Audiograms were made prior to training. All those developing aero-otitis media were sent for repeat audiograms as well as a thorough examination with the nasopharyngoscope. Not only those candidates that complained of ear difficulty but all candidates were checked for aero-otitis media, for it was noted that only about one-third ever complained of any disturbance. Some of these probably had symptoms but, because of fear of being rejected, did not mention any symptoms of aero-otitis media, and others failed to mention any trouble because they suffered very little discomfort.

About 30 percent of this 3000 developed aero-otitis media to some degree. Shilling and Teed[4] have found this percentage to be a little less in summer and a little higher during the cold months.

Preliminary nasopharyngoscopic examination of our cases discloses that almost 98 percent of those who later develop aero-otitis media had lymphoid hyperplasia blocking and crowding the

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[2] J. E. G. McGibbon, A. C. P. Campbell, E. D. Dickson, J. Laryngology and Otology 465 (December 1943).

[3] Eva Thompson, Howard A. Howe, Walter Hughson, Am. J. Physiol. 110, No. 2 (December 1934).

[4] Charles W. Shilling and Ira A. Everley, U. S. Navy Medical Bull. (January 1942); R. Wallace Teed, U. S. Navy Medical Bull. (February 1944).

eustachian tube. It seems clear that the mechanical action of this excess tissue may prevent proper ventilation. However, a certain number of cases which exhibited rather extensive lymphoid hyperplasia were able to withstand increased pressure without ever developing aero-otitis media. Among those of us who have been attempting to predict the occurrence of aero-otitis media in particular subjects, it is a common fact that certain men with enormous amounts of lymphoid tissue completely covering the eustachian orifices are able to withstand repeated exposures to 50 pounds of pressure (3.4 atmospheres) without developing aero-otitis media. It is significant to note that of those who develop aero-otitis media, almost all have a history of symptoms of obstruction and evidence of crowding in the nasopharynx; while of those not developing aero-otitis media, only 43.6 percent report previous symptoms of obstruction and show evidence of crowding in the eustachian tubes.

The treatment of lymphoid hyperplasia by radiation, whether radium, radon, or x-ray is not new. It has been extensively used at the Johns Hopkins Hospital, Baltimore, for more than 15 years by Crowe[6] and his associates. His technique is to apply a 50-mg radium applicator of 0.3-mm monel metal which is inserted in the inferior meatus to the region of the eustachian tube on each side for 8 minutes and 30 seconds. This procedure is repeated every 25 days until the lymphoid mass is reduced in size and the eustachian tubes are free and open. The number of treatments depends upon the appearance of the nasopharynx. At least three treatments are given. There are no ill effects from this amount of radiation, which is well within the limits of a safe dosage. Even an exposure of twice the regular dose would have little or no unfavorable effects. There is no more discomfort than would be experienced from a sunlamp treatment to develop that winter tan.

When the nasopharynx and the eustachian tube have been cleared of lymphoid tissue by treatment, these men are again subjected to pressure. In those that have completed radium treatment, there is only 8 percent incidence of aero-otitis media. Those cases who have not had any kind of treatment show over 80 percent recurrence.

It is interesting to note that contrary to the findings in the aviation group, cases of aero-otitis media in the submarine service show very little deafness except in cases of non-air containing middle ears (No. 5 ears). Those that are air-containing, with bubbles seen through the drums, show at most only 5–10 db loss of hearing. The eardrums of the flyers show marked retraction and loss of hearing, while the drums of submarine men are bulging except in the cases mentioned above. This difference is due to the "inflation" of the expansion of air trapped in the middle ear occurring on return to the surface. This also accounts for the difference in the appearance of the drums.

[6] S. J. Crowe and Curtis F. Burnam, Ann. of Otology, Rhinology, and Laryngology **50**, 15 (1941).

Auditory Acuity in Severe Aero-Otitis Media

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(Received June 1, 1945)

WHEN the eustachian tube "locks" so that an ear is subjected to differential barometric pressure across the eardrum, it will exhibit the otopathology described by Dr. Haines. The damage is described on a 5-point scale, 4 being the most severe. This paper will confine itself to a consideration of the change in acuity of those ears suffering damage of the most severe type.

It is commonly stated that deafness is a usual concomitant of barotrauma. As a matter of fact, however, we have found in the case of several score ears suffering rather severe otopathology—that is, No. 4 ears—only a half-dozen which show any noticeable decrement of acuity. Some individuals show rather severe loss, but as we shall show, the loss in these cases can be referred to the presence of fluid in the middle ear, and is not directly related as such to the vascular engorgement, interstitial hemorrhages into the eardrum, perforations of the eardrum, and the other changes which form the clinical picture of severe otitic barotrauma.

For all subjects reported here the procedure, unless otherwise stated, was as follows: a 6-octave audiogram was given in a soundproof room; the next day the subject was given the 50 lb. dry pressure test, and was sent immediately thereafter to the sound laboratory where a post-pressure audiogram was taken under the same conditions as the pre-pressure audiogram.

Figure 1 shows the average change in acuity for a group of 93 No. 4 ears. The zero line represents the pre-pressure audiogram, so that plots below this line represent a loss in acuity following pressure. For comparison, Fig. 1 also shows the average acuity change for 40 ears identically treated but diagnosed as No. 0, that is, in which little or no otopathology was to be seen.

Whether the No. 4 ears are compared with their pre-pressure state or compared with a control group, it is clear that sound transmission is not greatly affected. It seems incontrovertible that the clinical syndrome of aero-otitis media as it is seen on otoscopy does not always produce and is not highly correlated with acuity loss.

It might be thought that in the 93 No. 4 ears of Fig. 1 there were a number of cases showing loss, the extent of which is concealed by the fact that there were also cases showing gain. This is conceivable since an improvement in acuity is sometimes found, possibly as a result of the drainage through the eustachian tube of effusion previously collected in the bottom of the middle-ear. A glance at Fig. 2, however, where through each average a line is drawn representing $\frac{2}{3}$ of the cases, will show that there were very few cases which lost more than 10 db at any frequency.

Figure 3 shows the loss for the No. 4 subject who showed the greatest decrement. This pre-test audiogram is drawn as the zero line. Figure 4 shows a case of actual improvement. Losses of the magnitude shown in this group cannot be described as disabling; evidently the average data for No. 4 ears are not concealing any examples of critical loss.

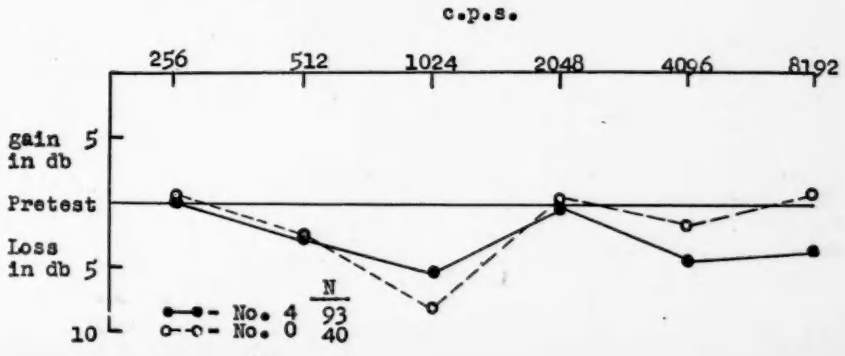

FIG. 1. Acuity loss for No. 4 and for No. 0 ears.

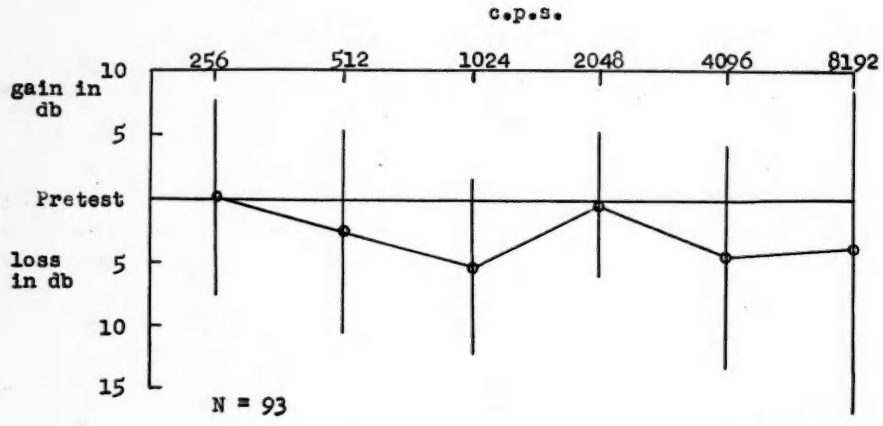

FIG. 2. Acuity loss for No. 4 ears±standard deviation.

This is not to say, however, that severe loss in acuity is not associated with the syndrome. There are cases in our files of individuals who have suffered losses of 50 and even 60 db at certain frequencies. It will shortly be explained why these cases have been put in a separate group.

In attempting to understand why certain No. 4 ears show rather severe loss while others do not, it was supposed at first that those which exhibited loss may well have suffered damage to the labyrinth. When this possibility was mentioned to Dr. Stacy Guild, however, he stated (personal communication), "The variations in functional effect are so great, from seemingly pure middle-ear lesions, that I do not believe it necessary to assume inner-ear lesions . . . to explain marked degrees of hearing impairments in some men with acute Aero-Otitis Media. I grant, however, that the hypothesis cannot be ruled out of consideration by any evidence I know of."

The next most obvious possibility was, that subjects whose ear drums were ruptured would show the greater losses. Not only did this prove *not* to be the case, but when the average change for all uncomplicated perforated ears was obtained, it was found that perforations in and of themselves have only a minor effect on acuity.

Figure 5 presents the average loss for ears in which the most conspicuous vital change was perforation. A decrement tendency is seen of the order of 5 to 10 db; but these cases are not those showing the severest loss.

On closer analysis of the pathology as de-

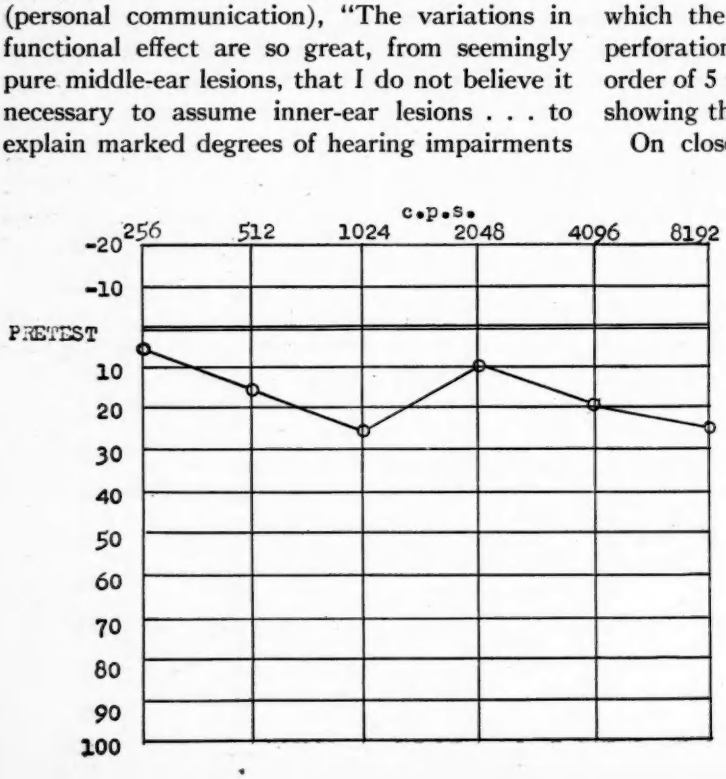

FIG. 3. Shows extreme loss for No. 4 ears. Remarks: R ear = No. 4.

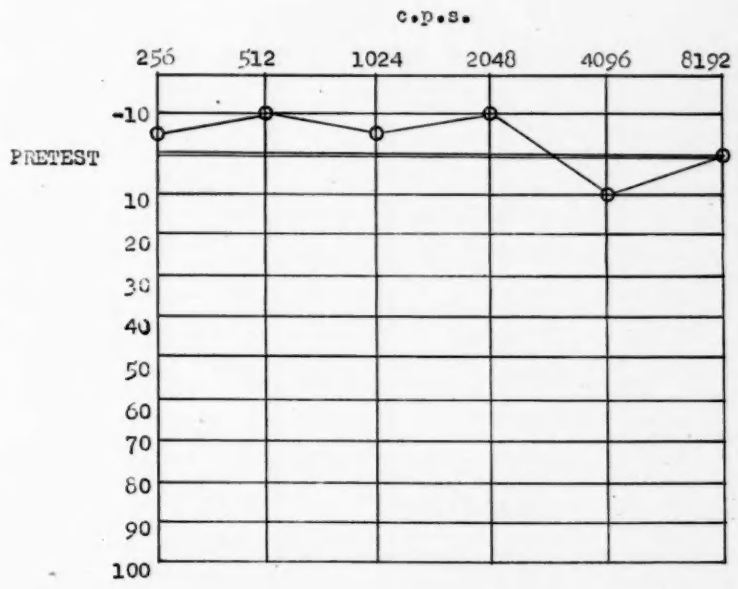

FIG. 4. Shows improvement for No. 4 ear.
Remarks: Right ear = No. 4.

scribed by the otologist, it was noticed that the subjects who showed the severer losses most often were those in which the middle ear contained no air, but only free blood and serum. When the audiogram data was inspected from this point of view, it seemed that we had finally come upon the cause of deafness in those subjects with deafness as the striking functional change.

In order to study more fully this possibility, we began the practice of differentiating from other No. 4 ears, those ears in which it could be determined from otoscopy that the middle-ear was filled with transudate. These latter ears are now being labeled No. 5, and are being studied more intensively with respect to the period of recovery of acuity.

It will now be stated that Fig. 1, in which the loss for No. 4 ears was shown to be negligible, did not contain any of the No. 5 ears.

Figure 6 presents the loss for a group of No. 5 ears. It must be emphasized that these ears do not show a greater amount of pathology than the No. 4 ears of Fig. 1—the essential difference is merely the presence of free blood in the tympanum. The loss in these No. 5 ears is immediate and striking.

Figure 7 presents the loss in a typical No. 5 ear. In this figure the pre-pressure audiogram is given in absolute terms since there may be the possibility that ears which at some points are already low may suffer further loss at those particular frequencies.

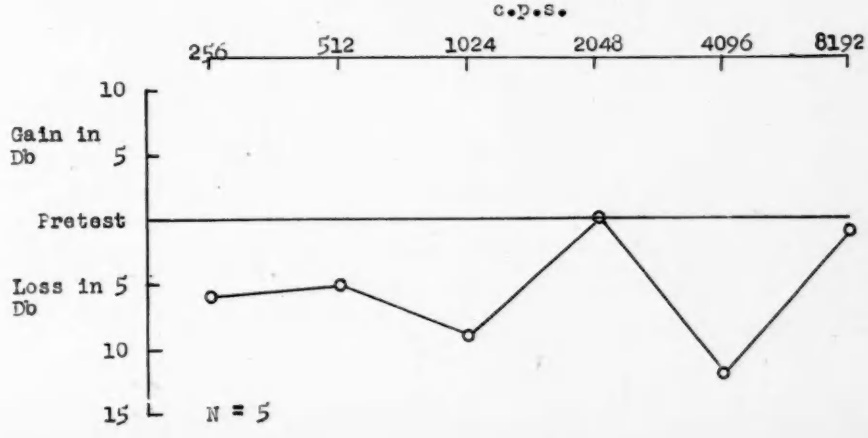

FIG. 5. Acuity loss for perforated ears.

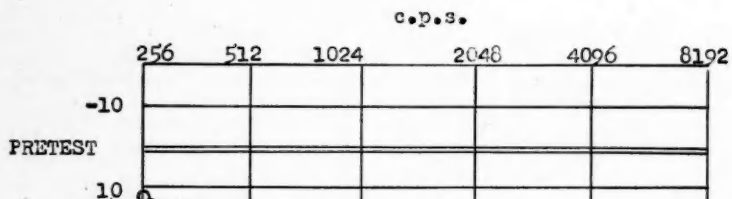

FIG. 6. Shows average loss of acuity for No. 5 ears.

It is more than likely that this group can be directly compared in terms of pathology with Shilling and Everley's 18 most severe cases of aero-otitis media, published in 1942. In this series of 18 cases, the losses from 128 to 8192 c.p.s. ranged from 12.7 to 23.9 db. Our No. 5 ears compare in general with this magnitude of loss.

When, furthermore, the case histories of the patients of Shilling and Everley were analyzed with the latter's help, among the 18 most severe cases was evidence that the middle ears of some of these cases contained appreciable quantities of free blood. Such expressions as "drum a dark purple" are found in the protocols. These authors as well as Dr. Haines of the present study state that they have seen the level of blood in the tympanum to be clearly discernible as a straight line across the ear drum, the line shifting as the head is tilted.

In view of the data reported here, and in the absence of evidence to the contrary, the hypothesis is offered that the pathological condition of the structures of the ear in acute aero-otitis

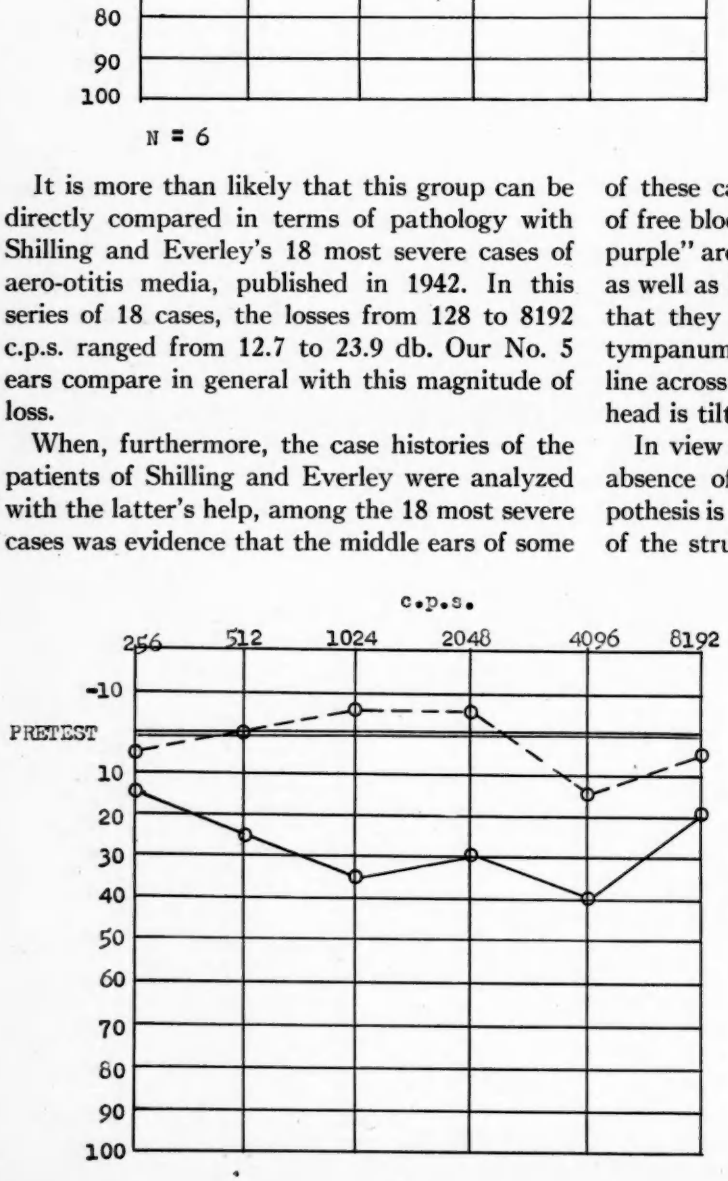

FIG. 7. Shows loss for typical No. 5 ear. Remarks: Right ear = No. 5.

media does not of itself bring about greatly lowered acuity; that where appreciable decrement does occur it is brought about by the dynamics of fluid in the tympanum.

A striking difference is observed between the acuity data in barotrauma which we have collected and that reported by the Air Forces, the latter commonly reporting much greater incidence and magnitude of deafness. This is the more striking in that our recompression chamber subjects the men to 3.4 atmospheres pressure—a figure much higher than Air Force personnel ever receive either in the field or experimentally. It would ordinarily be assumed that with our more severe conditions, our incidence of deafness would be greater.

But it must be remembered that Air Force personnel are studied under somewhat different conditions from ours. In the first place, Air Force subjects receive change in pressure on every flight, whereas the data reported in this paper have been collected almost exclusively from a single pressurizing; and it is almost certainly true that the repeated application of our experimental conditions would result in a greater amount of barotrauma, and, one would expect, a greater loss in acuity likewise.

In the second place, the typical Air Force experiment consists in a decompression run, whereas, in our chamber, compression is undertaken. There will be differences in vascular engorgement and consequent vascular rupture according to whether the pressure in the vascular bed and surrounding fluids is greater or less than in the middle ear sealed by a non-patent eustachian tube. Air Force conditions are such that more vascular rupture should occur there than under our conditions.

In the third place, two factors in a sense extraneous to the central argument may complicate interpretation of acuity data in the Air Forces; I refer (a) to the effects on acuity of middle-ear pressure in and of itself and (b) to auditory fatigue.

It is well known that a negative pressure in the middle ear, by pulling in both drumhead and stapes telescopes the whole ossicular chain and impairs conduction immediately. The interpretation of any test of acuity, then, run *during the course of* a pressurizing, must carefully distinguish between the reduction of acuity owing to pressure and that which is possibly owing to barotrauma.

Likewise the precise amount of acuity loss caused by exposure for long periods to very high sound intensities will need to be distinguished carefully from the loss owing solely to barotrauma. Since it is known that the effects of auditory fatigue may persist for many hours, it would seem particularly hard in these circumstances to assign a true value to acuity loss owing solely to the otitic syndrome. It is possible that certain statements to the effect that deafness is a common aspect of aero-otitis media have not taken some of these considerations fully into account.

Tentative Code for Measurement of Performance of Hearing Aids

COMMITTEE OF THE AMERICAN HEARING AID ASSOCIATION

These specifications for methods of measurement of hearing aids were drawn up by a technical committee organized by the American Hearing Aid Association, including engineering representatives from most of the larger manufacturers of hearing aids as well as technical representatives from non-commercial groups who have been working in this field. It is believed that these specifications represent the best of present practice, although additions may be made later to cover further material such as methods of applying correction factors for the baffle effect of the body of the wearer, for the difference between the pressure and the free field characteristics of the ear, and for possible leakage of sound between the ear and the ear insert, as well as standardized methods of measurement of instruments with bone conduction receivers and of carbon type hearing aids. Since sufficient information is not yet available to reach definite conclusions on these points, the code is offered in its present form for consideration by those interested in this subject.

FRED W. KRANZ, *Chairman Technical Committee*
American Hearing Aid Association
Elmsford, New York

1.0 SCOPE OF SPECIFICATIONS

THIS specification is concerned with methods of measurements of the over-all acoustical performance of an air-conduction hearing aid.

1.1 Acoustical data shall be given in terms of r.m.s. sound pressure, expressed in decibels relative to a reference level of 0.0002 dyne per square centimeter.

2.0 GENERAL METHOD OF MEASURING ACOUSTICAL GAIN

The general method is to:

2.1 Produce a suitable sound field.

2.2 Measure the sound intensity at a suitable point in the sound field, using a calibrated microphone.

2.3 For the above microphone, substitute the transmitter of the hearing aid under test and measure the acoustic output of the hearing aid receiver.

2.4 A comparison of the results of 2.2 and 2.3 will give the over-all acoustical gain of the hearing aid.

3.0 TEST ROOM

3.1 The enclosure used for testing shall provide substantially free field conditions over the test frequency range, for the sound source and hearing aid positions used, and shall have a satisfactorily low ambient noise level.

3.2 Free field condition shall be defined as a condition such that the influence of standing waves is negligible. This may be determined by measurement of the inverse distance-pressure relation between sound source and microphone. This relation shall be within 2 db of the theoretical value. This determination shall be made using a sound source of substantially point character.

3.3 Noise level in the enclosure shall be at least 20 db below the level of the weakest test tone to be used, as measured with microphone and equipment substantially equivalent to that specified in Section 5.0. (Note: It may be convenient to use filters to reduce the effect of external disturbances outside the test frequency range.)

3.4 All tests on the hearing aid shall be made with the hearing aid at a temperature of 80°F±5° and the actual temperature of each test shall be recorded on the data sheet.

4.0 SOUND SOURCE

The sound source for hearing aid testing shall consist of an oscillator, amplifier and loudspeaker (or artificial mouth). An electrical equalizer may be included in the system if desired, to assist in producing a uniform acoustical response over the desired frequency range.

4.1 The oscillator shall be of the continuously adjustable frequency type. Maximum error of the frequency calibration shall not be over 2 percent.

4.2 Distortion in the oscillator, amplifier, and loudspeaker combined shall be such that no single harmonic component in the sound produced shall have an amplitude in excess of 3 percent of that of the fundamental at the sound pressures used for frequency response tests.

4.3 Signal to noise ratio of the oscillator-amplifier combination shall be at least 55 db for the levels to be used in the tests.

4.4 The relation between the loudspeaker and the hearing aid under test shall be such as to minimize inter-reflection and interference effects.

5.0 MEASUREMENT OF THE SOUND FIELD

Measurement of the sound field shall be made by the use of a high quality microphone and suitable amplifying and measuring equipment. The calibration of the amplifying and measuring equipment shall be accurate within 1 db.

5.1 The microphone shall be provided with a free field calibration made by an acceptable laboratory, and be used as specified by the calibrating laboratory. Without prejudice to others, the following have been suggested as acceptable laboratories:

National Bureau of Standards, Washington, D. C.

Harvard University, Cambridge, Massachusetts.

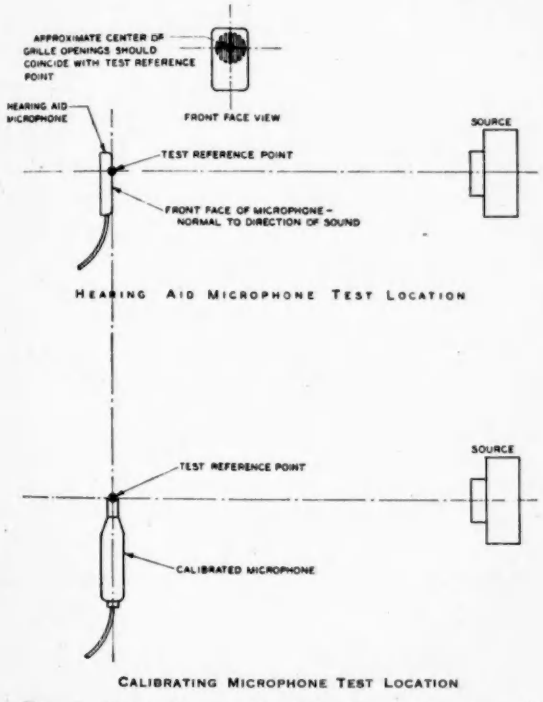
APPROXIMATE CENTER OF GRILLE OPENINGS SHOULD COINCIDE WITH TEST REFERENCE POINT
FRONT FACE VIEW
HEARING AID MICROPHONE
SOURCE
TEST REFERENCE POINT
FRONT FACE OF MICROPHONE - NORMAL TO DIRECTION OF SOUND
HEARING AID MICROPHONE TEST LOCATION
SOURCE
TEST REFERENCE POINT
CALIBRATED MICROPHONE
CALIBRATING MICROPHONE TEST LOCATION

FIG. 1. Note: Center of calibrating microphone diaphragm should coincide with test reference point. *Correct orientation of microphone with respect to direction of sound must be obtained from calibrating laboratory.*

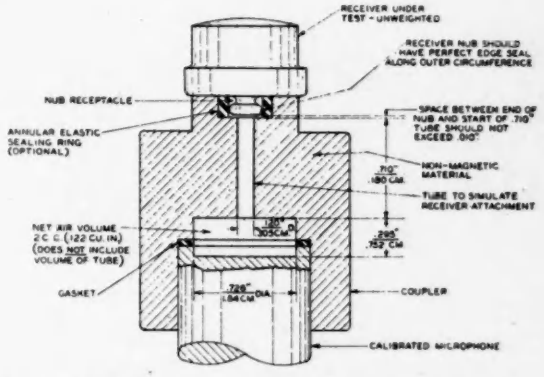
RECEIVER UNDER TEST - UNWEIGHTED
RECEIVER NUB SHOULD HAVE PERFECT EDGE SEAL ALONG OUTER CIRCUMFERENCE
NUB RECEPTACLE
ANNULAR ELASTIC SEALING RING (OPTIONAL)
SPACE BETWEEN END OF NUB AND START OF .710" TUBE SHOULD NOT EXCEED .010"
.710" 1.80 CM
NON-MAGNETIC MATERIAL
TUBE TO SIMULATE RECEIVER ATTACHMENT
NET AIR VOLUME 2 C C (.122 CU IN.) (DOES NOT INCLUDE VOLUME OF TUBE)
.120" 3.05 CM
.295" .752 CM
GASKET
.729" 1.84 CM DIA
COUPLER
CALIBRATED MICROPHONE

FIG. 2. Artificial ear for small hearing aid type receivers.

5.2 It is suggested that the microphone used be small enough to produce a minimum disturbance of the sound field because of its presence, and be of maximum practical stability.

5.3 The microphone shall be placed in the same location that the hearing aid will later occupy. (Note: See Fig. 1.)

6.0 ARTIFICIAL EAR AND ASSOCIATED EQUIPMENT

6.1 An air-conduction receiver of the type normally coupled to a conventional molded insert fitted into the ear canal shall be coupled to a 2-cc artificial ear whose essential dimensions shall be those given in Fig. 2.

6.2 The receiver shall rest upon the upper part of the 2-cc artificial ear without weighting, the connection between being made by a tight seal between the outer diameter of the nub of the receiver and the nub receptacle of the artificial ear. Common petroleum jelly or wax may be used to improve the seal.

6.3 The 2-cc volume indicated on the drawing shall be the volume between the lower end of the tube and the surface of the microphone diaphragm. If the microphone has a grill, the volume of the solid part of the grill shall not be included in the 2 cc.

6.4 Receivers not using ear inserts shall be coupled to a 6-cc closed coupler artificial ear of

acceptable type. A non-magnetic weight of 1 kilogram shall be used to insure good seal of ear to receiver. A soft cushion may be used between the weight and the receiver, if desired.

6.5 Sections 6.6, 6.7, 6.8, and 6.9 shall apply to both 2-cc and 6 cc-artificial ears.

6.6 The microphone used shall have a diaphragm of high mechanical impedance, essentially equivalent to that of a miniature condenser microphone.

6.7 The calibrated microphone used shall be provided with a pressure calibration by an acceptable laboratory. This shall be considered the calibration of the artificial ear.

6.8 The outer casing of the artificial ear coupler shall be of such type and thickness of non-magnetic material as to be essentially rigid.

6.9 The output of the artificial ear shall be measured by a high quality amplifier-voltmeter of either the direct-indicating or recording type, and any error shall be known and allowed for within 1 db.

7.0 MOUNTING OF HEARING AIR FOR TEST

7.1 The mechanical support of the hearing aid shall not introduce spurious effects because of mechanical resonances or mechanically transmitted vibrations.

7.2 The basic measurements shall be made with the hearing aid held in the sound field without baffle and graphs made of the results.

7.21 The support for the hearing aid shall be of such size and character that it does not appreciably disturb the sound field in the vicinity of the hearing aid.

7.3 It is desirable to provide characteristic curves which include the baffle effect of the human body.

7.31 If in addition to the results of 7.2, measurements are made with the use of a body-simulating baffle, the results so obtained may be shown, and in such a case, specifications for the baffle construction and the position of the hearing aid on the baffle shall be given.

7.32 If desired, a curve may be shown based on the measurements of Section 7.2, but including a correction for average body-baffle effect applying to the particular hearing aid being tested as determined by measurements on a minimum of ten people. Such a curve is to be properly identified.

8.0 METHOD OF DETERMINATION OF FREQUENCY RESPONSE AND MAXIMUM ACOUSTICAL GAIN

Measurement of the frequency response shall be made on the foregoing specified equipment in the following manner:

8.1 Adjust the sound field to 60 db at the point where the hearing aid and body-simulating baffle (if used) is to be placed.

8.11 It is contemplated that the sound pressure is not to be changed throughout the test; but, if the test is made by continuous variation of frequency, slight variations of pressure may ensue, caused by variations in speaker sensitivity. Such variations from 60 db shall not exceed ± 3 db. These variations shall be allowed for in computing the results.

8.2 The center of the front face of the hearing aid microphone grill must coincide in location with the center of the diaphragm of the calibrating microphone. The face of the microphone of the hearing aid shall be normal to the line from it to the sound source. See Fig. 1. Positive and accurate locating means shall be used.

8.3 After the hearing aid is positioned as indicated in Section 8.2, adjust the volume control so that with an air-conduction receiver the pressure in the artificial ear is approximately 100 db at the frequency of greatest response of the hearing aid. If the gain of the hearing aid is insufficient to give this output without overload, measurement shall be made of greatest available output which will not create overload, with the input of 60 db. For the purpose of this test, an instrument will be considered to be operating at no overload if the acoustical output at the frequency of maximum measured distortion between 200 and 5000 cycles does not contain more than 10 percent r.m.s. total harmonic distortion.

8.31 Carbon type hearing aids shall be tested at the nominal operating voltages recommended by the manufacturer for normal use.

8.32 Vacuum tube hearing aids shall be tested at an "A" battery voltage of 1.25 volts per

cell, and at the nominal "B" battery voltages recommended by the manufacturer. "C" battery, if used, shall be of voltage recommended by the manufacturer for the "B" voltage used in this test.

8.4 Measure the receiver output at frequencies of 200 to 5000 cycles, with no change of sound field pressure. If this measurement is made by continuous change of frequency, at least ten seconds per octave shall be taken for covering the above range. For manual recording, take the response curve point by point within the frequency range indicated above in sufficient detail to establish definitely the shape of the curve.

8.41 No output pressure level reading shall be considered valid unless the reading drops by 15 db or more when the signal input is cut off.

8.5 The artificial ear sound pressure level, as taken in 8.4 shall be plotted against frequency on semilogarithmic graph paper. Frequency shall be marked along the logarithmic X axis, and relative response in decibels with the 1000 cycle value taken as zero along the linear Y axis. The curve, after all specified corrections have been made, may be smoothed graphically; but the final curve shall not deviate by more than 4 db from any measured point, nor shall the distance on the frequency scale between successive intersections of the final curve with the original unsmoothed curve be greater than 5 percent of the mean frequency of the band between the intersections.

8.51 The paper used to graph the response curves shall be so proportioned that 45 db shall equal one logarithmic frequency cycle in length.

8.6 The maximum acoustical gain curve shall be taken in the same manner as the frequency response curve described above, except that the volume control shall be turned up to its maximum setting and the input pressure reduced sufficiently to avoid overload distortion as defined in Section 8.3. The results shall be plotted in terms of the difference between acoustic input level used and the recorded acoustical output levels. This maximum acoustical gain curve may be obtained by use of the gain data of Section 8.4, with corrections for the amount of increase in gain resulting when the volume control on the hearing aid is advanced from its setting during the frequency response test to its maximum setting, under non-overload conditions.

Evidence is in hand showing that the human body affects instrument response and the problem of using a body-simulating baffle in tests is to be given further study. Evidence is likewise available showing that the difference between the pressure and free field characteristics of the ear requires further study to arrive at accurate correction values. A similar situation is recognized with respect to leakage of sound between the ear and the ear insert.

9.0 DETERMINATION OF EFFECT OF BATTERY VOLTAGE VARIATION

The object of this test is the determination of the effect of battery voltage variation on acoustical gain of a vacuum tube hearing aid.

9.1 The general test conditions shall be as specified in Section 8, except as otherwise specified below.

9.2 The instrument shall be positioned and adjusted as in Sections 8.2, 12.1, and 12.3.

9.3 With the "A" circuit potential maintained at 1.25 volts per cell of "A" battery, the acoustical gain at 600 cycles shall be measured at various "B" battery voltages. The "B" battery voltage shall be varied from the greatest nominal voltage specified by the hearing aid manufacturer to two-thirds the minimum nominal voltage, using a tapped battery and not a rheostat for the purpose. The particular type of battery used, as well as its physical location, shall be such as is recommended by the hearing aid manufacturer in such instances as he indicates this to be of importance.

9.4 The result shall be plotted as a graph of "B" voltage (along the X axis) *versus* deviation of the acoustical gain from the value at the greatest nominal voltage (along the Y axis).

9.5 With the "B" battery voltage set at each nominal value recommended by the hearing aid manufacturer for normal use, and also at two-thirds of the minimum nominal voltage (See Section 9.3), acoustical gain shall be measured at various "A" circuit voltages. The "A" voltage

shall be varied from 1.5 volts per "A" cell to 0.8 volts per "A" cell, using a method which will only simulate internal resistance in the "A" battery and will not add other regenerative effects. (Note: A satisfactory method to achieve this is to use a run-down "A" battery of the type usually used with the instrument.)

9.6 The result shall be plotted as a graph of "A" circuit voltage (along the X axis) *versus* deviation of acoustical gain from its value at 1.5 volts per "A" cell (along the Y axis).

10.0 METHOD OF MEASURING NON-LINEAR DISTORTION IN VACUUM TUBE INSTRUMENTS

The object of this test is to determine the relation between the acoustical output of a hearing aid and the non-linear distortion products present in that output, introduced by the hearing aid.

10.1 The general method is to:

10.11 Produce a sound field of suitable intensity and purity at a predetermined point in a suitable enclosure.

10.12 Place the transmitter of the hearing aid under test at this predetermined point, and measure the acoustic output of the hearing aid receiver.

10.13 A suitable analysis of the acoustic output will give the result desired.

10.2 The test apparatus shall conform to the following requirements:

10.21 The test room shall be as described in Section 3.

10.22 The sound source shall be as given in Sections 4.0, 4.1, 4.2, 4.3, 4.4, except that no single harmonic component in the sound produced shall exceed 0.5 percent of the fundamental at the sound pressures used for this test.

10.23 The sound field shall be measured as described in Section 5.

10.24 The acoustical output shall be fed to an artificial ear and associated equipment as described in Section 6, except as modified by Sections 10.25 to 10.28.

10.25 The calibrated microphone used in the artificial ear and its associated amplifier shall have negligible distortion for the output sound pressures used.

10.26 The combined response of the calibrated microphone used in the artificial ear and its associated amplifier, that is, the voltage delivered to the input terminals of the distortion meter or wave analyzer for a constant sound pressure at the microphone diaphragm, shall be uniform to within 1 db over the frequency range 200 to 5000 cycles. Any variation greater than this shall be allowed for.

10.27 When determining the total output sound pressure, the output of the artificial ear amplifier shall be measured using a meter which gives essentially the same readings as an r.m.s. meter. (Note: Until such time as satisfactory durable r.m.s. meters are commercially available, it shall be permissible to use a meter which will indicate average voltage and is free from "turnover" error.)

10.28 The analysis of the output of the artificial ear amplifier shall be made using a good quality distortion meter or wave analyzer.

10.29 The percentage total harmonic distortion shall be considered as

$$100\left(\frac{E_2^2+E_3^2+E_4^2+\cdots}{E_1^2+E_2^2+E_3^2+E_4^2+\cdots}\right)^{\frac{1}{2}}$$

where E_1 is the amplitude of the voltage of the fundamental frequency in the output of the amplifier of the artificial ear, and E_2, E_3, etc. are the amplitudes of the voltages of the harmonic frequencies.

10.3 The measurement shall be made by placing the hearing aid in a sound field whose pressure level at the position in which the aid is to be placed is 60 db, coupling the receiver to the proper artificial ear, adjusting the acoustical output to any predetermined point by means of the volume control of the hearing aid, then measuring the character of the electrical output of the artificial ear.

10.31 Tests of vacuum tube hearing aids shall be run with sound fields of at least 600 cycles, 800 cycles and 1000 cycles.

10.32 Such tests shall be run at output pressures ranging from 80 db up to that accompanied by 20 percent distortion, or, if this is not possible, up to the maximum output available.

10.33 This measurement shall be duplicated with an input sound pressure of 75 db.

10.4 The test results shall be plotted as a graph of sound output in decibels along the *X* axis against r.m.s. distortion (in percent) along the *Y* axis.

10.41 The paper used to graph the results shall be so proportioned that 20 db along the *X* axis shall be equal in length to 10 percent along the *Y* axis.

11.0 METHOD OF MEASURING ACOUSTIC INPUT-OUTPUT CHARACTERISTICS

The object of this test is a determination of the relation between the acoustic input and the acoustic output of a hearing aid with the volume control at a fixed position. Since this relation is intended primarily as a measure of effectiveness in suppressing loud sounds, rather than an indication of usable output, distortion is overlooked.

11.1 The general method is to be:

11.11 Produce a sound field of suitable intensity, purity, and frequency at a predetermined point in a suitable enclosure.

11.12 Place the transmitter of the hearing aid under test at this predetermined point, and place the receiver of the aid on a suitable artificial ear.

11.13 Set the volume control by appropriate procedure.

11.14 Make a record of the acoustic output of the receiver at various values of the sound field.

11.2 The test apparatus shall be as follows:

11.21 The test room shall be as described in Section 3.

11.22 The sound source shall be as given in Sections 4.0, 4.1, 4.2, 4.3, and 4.4.

11.23 The sound field shall be measured as described in Section 5.

11.24 The acoustical output shall be fed to an artificial ear and associated equipment as described in Sections 6 and 10.27.

11.25 In a vacuum tube hearing aid, the *A* circuit potential shall be maintained at 1.25 volts per cell of "A" battery. The "B" battery voltage may be adjusted to any nominal voltage specified by the hearing aid manufacturer, using a tapped battery and not a rheostat for the purpose.

11.26 In a carbon hearing aid, the battery voltage shall be adjusted to any nominal voltage specified by the hearing aid manufacturer.

11.3 The measurement shall be made by placing the hearing aid in a sound field whose sound pressure level is adjusted (in an adequate number of steps) over the range of 50 to 90 db, and reading the corresponding acoustical outputs in the range of 80 db to 140 db, or over such part thereof as the hearing aid will cover.

11.31 The tests will be run with sound fields of 600, 1000, 2000, and 3000 cycles.

11.32 One series of tests shall be made with the volume control at maximum setting.

11.33 In order to simulate the typical user's adjustment of the hearing aid to give the desired impression of loudness, the tests shall be repeated with the volume control at such a setting as will give 100 db output with a 60-db 600-cycle free field input, with the tone control at the setting to be used in the measurement. If the maximum output of the instrument is not great enough to do that, this part of the test shall be omitted.

11.34 If time limitations have an effect on the results of these tests, suitable provision shall be made to avoid such effects. It is suggested in this situation that each reading be taken by maintaining the test room silent for at least 10 seconds, applying the sound field, then taking the output reading within two seconds

11.4 Results shall be plotted with input along the *X* axis and output along the *Y* axis. Graph

shall contain full information on all variable element settings, especially "B" battery voltage and tone control setting.

12.0 METHOD OF MEASUREMENT OF BATTERY DRAIN

The object of this test is the determination of battery drain under operating conditions, when actually delivering acoustical output.

12.1 When a vacuum tube unit is tested, "B" and "C" battery conditions shall be the combinations recommended by the hearing aid manufacturer. "A" supply voltage shall be 1.25 volts per cell.

12.11 For a carbon type of instrument the voltage shall be that recommended by the manufacturer for normal use.

12.2 In order to simulate the typical user's adjustment of the hearing aid to give the desired impressions of loudness, the instrument shall be placed in a 600 cycle 60 db sound field, with the receiver coupled to the appropriate artificial ear.

12.3 The volume control shall be adjusted to make the receiver acoustical output 100 db. If the maximum available output is less than this, the volume control shall be set at maximum.

12.4 The battery drain shall then be measured using instruments whose error is not over 1 percent at the part of the scale used for the measurement.

13.0 MEASUREMENT OF VARIATION OF GAIN WITH TEMPERATURE AND HUMIDITY CHANGES

It is recognized that some hearing aids vary in performance with changes in temperature and humidity. In the present state of the measuring art it is difficult to specify satisfactory methods of measurement. It is hoped such specifications can be added to this code later.

Addendum on Singing Flames

ARTHUR TABER JONES
Smith College, Northampton, Massachusetts

THE following additional statement should have been made on page 264 of my recent paper on Singing Flames.[1]

In accordance with the hypothesis advanced in that paper, and for the case where the gas tube ends below in a flask, the mid positions of such regions of silence as those found by Sondhauss are to be expected to occur [page 262] when the length of the gas tube is an odd number of quarter wave-lengths. Making use of the values on page 257, and assuming that the hydrogen used by Sondhauss was pure, we find that for his first region of silence the lengths of the gas tube centered around 0.28λ, and for the second around 0.70λ. On Rayleigh's theory these regions should center around 0.38λ and 0.88λ. By assuming that the hydrogen used by Sondhauss was not pure, satisfactory agreement was obtained with Rayleigh's theory [page 257]. Without that assumption the results obtained by Sondhauss are in better agreement with the modified theory that I have suggested than with that given by Rayleigh.

[1] A. T. Jones, J. Acous. Soc. Am. **16**, 254 (1945).

Acoustical Society News

Change of Editor's Address

Your Editor, having spent many years in instructing the young, can henceforth be reached at 3318 Fessenden Street NW, Washington 8, D. C., phone WOodley 3318, from which address he will engage in divers activities.

Science—The Endless Frontier

If, by the time you receive this issue you have not seen a copy of "Science—The Endless Frontier, a Report to the President on a Program for Post War Scientific Research" by Vannevar Bush, Director of the Office of Scientific Research and Development, I would highly recommend that you obtain a copy by writing to the United States Government Printing Office at Washington.

The report was written in response to a letter from President Roosevelt who requested recommendations on the following points:

"1. What can be done consistent with military security and with the prior approval of the military authorities to make known to the world as soon as possible the contributions which have been made during our war effort to scientific knowledge?

"2. With particular reference to the war of science against disease, what can be done now to organize a program for continuing in the future the work which has been done in medicine and related sciences?

"3. What can the Government do now and in the future to aid research activities by public and private organizations?

"4. Can an effective program be proposed for discovering and developing scientific talent in American youth so that the continuing future of scientific research in this country may be assured on a level comparable to what has been done during the war?"

A number of committees composed of eminent scientists, administrators, and doctors were appointed by Dr. Bush to study these problems and the report has been synthesized from their findings.

The report recommends that the Government should accept new responsibilities for promoting the flow of new scientific knowledge and the development of scientific talent in our youth. It is estimated that because of the war there is a deficit of 150,000 science and technology students at the Bachelor-degree level and a further deficit of 17,000 who would have obtained advanced degrees in these fields, but for the war. The more favorable salaries in applied science positions are tending to draw the trained scientists from the colleges, universities, and research institutes where basic research is performed; civil service salaries for government scientists are also inadequate. It is felt that library facilities in the sciences could be very much improved.

To assist in alleviating these difficulties the report recommends that a "National Research Foundation" be established by Congress with an appropriation of approximately $30,000,000 for the first year rising to the order of magnitude of $125,000,000 per year by the fifth year. This foundation "should develop and promote a national policy for scientific research and scientific education, should support basic research and non-profit organizations, should develop scientific talent in American youth by means of scholarships and fellowships, and should by contract and otherwise support long range research on military matters." The policies of the foundation would be governed by a board of nine members selected by the President. The foundation would appropriate funds to various established laboratories throughout the country for the purpose of supporting basic research in medicine and the physical and natural sciences; it would grant fellowships for the support of students and advanced scholars; it would grant funds for encouraging the publication of scientific knowledge, promoting international exchange of scientific information, and the extension of library services in the sciences.

Every scientist should study this report in order that he may be informed on this long range proposal concerning the manner in which research in the natural sciences may be organized in the future.

F. A. Firestone

Navy Establishes Research Laboratories at the Pennsylvania State College

The U. S. Navy has completed arrangements for the establishment of two permanent ordnance research laboratories which will be in operation by fall at the Pennsylvania State College under a Bureau of Ordnance contract. The establishment of these laboratories is in keeping with the Bureau of Ordnance broad policy of forming research affiliations with educational institutions to further development of naval weapons and for educational purposes in such military problems during the post war period.

The Ordnance Research Laboratory, dealing with underwater ordnance, will be housed in the new building now under construction on the campus. The work will be a continuation of the research formerly carried on by the Underwater Sound Laboratory at Harvard University which has been sponsored by the Office of Scientific Research and Development, with technical direction from the Bureau of Ordnance. Dr. Eric A. Walker, who was in charge of the Ordnance Research Division at Harvard, will direct the new laboratory and also head the Electrical Engineering Department of the College. Earlier, Dr. Walker was assistant professor of electrical engineering at Tufts College. He later was head of the Electrical Engineering Department at the University of Connecticut and was associated with the Doble Engineering Company and Colt Patent Fire Arms Company as a consultant. His research projects include work on the behavior of dielectrics at high voltages, the effect of moisture and aging on insulating oils, and development of certain classified weapons for the Bureau of Ordnance.

Assistant directors of the Ordnance Research Laboratory will be A. N. Butz, Jr., who formerly operated a private electronics research laboratory, R. R. Thompson, formerly

associated with Bell Telephone Laboratories and the Humble Oil and Refining Company, and Dr. Harvey Brooks. All of these men are now affiliated with the Harvard University Laboratory. A staff of approximately 125 scientists, technicians, and clerks will be transferred from the Harvard Laboratory to the new unit. In addition to the work that will be carried on in the Ordnance Research Laboratory on the campus, this laboratory will also operate a calibration station at the Black Moshannon Lake, approximately twenty miles from State College, and a test station at Fort Lauderdale, Florida.

The Petroleum Refining Laboratory has been in operation for approximately sixteen years at The Pennsylvania State College. During the present war emergency, it has also been under sponsorship of the Office of Scientific Research and Development. The plan is for this laboratory to continue with the petroleum research under a direct contract with the Bureau of Ordnance, including special work for and technical reports to the other services. Dr. M. R. Fenske will continue as director of the Petroleum Refining Laboratory, a position which he has held since it was established. Dr. Fenske's research has included catalytic gas reactions, synthesis of organic solvents and fuels, distillation and solvent extraction, production of special fuels and hydraulic fluids, lubricants, refining of oils, composition, analysis and separation of petroleum products. Assisting Dr. Fenske is Dr. Dorothy Quiggle and R. A. Rush. Dr. Quiggle has been with the Petroleum Refining Laboratory since it was established and Mr. Rush since 1932, both are faculty members of The Pennsylvania State College. The staff of the Petroleum Refining Laboratory includes more than fifty chemists, chemical engineers, and technicians.

The Ordnance Research Laboratory has been placed under the School of Engineering (H. P. Hammond, Dean) by The Pennsylvania State College, and the Petroleum Refining Laboratory is under the School of Chemistry and Physics (F. C. Whitmore, Dean). Most of the scientific and technical personnel will hold academic appointments on the faculty of the College.

New Members

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1785 Massachusetts Avenue
Washington 6, D. C.
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British Air Commission

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Wellesley 81, Massachusetts
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Harvard University
Cambridge, Massachusetts

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Harvard University
Cambridge, Massachusetts

David H. Cunningham
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Engineer, RCA

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Cambridge, Massachusetts

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Kalamazoo 99, Michigan
Physicist

Fellows	185
Members	902
Total Membership	1087

Current Publications on Acoustics

F. A. FIRESTONE
3318 Fessenden Street, NW, Washington 8, D. C.

Book Review

Introduction to Theoretical Seismology.

BY J. B. MACELWANE, S. J. AND F. W. SOHON, S. J. **Part I, Geodynamics.** BY J. B. MACELWANE, S. J. Pp. 366 + 1 folding chart. John Wiley & Sons, Inc., New York.

Although in the narrow sense acoustics is principally interested in the study of compressional waves in fluids, it has always devoted enough attention to elastic waves in solids to justify amply the review in this Journal of a book on seismic waves. The work here reviewed forms the first part of a two volume sequence on theoretical seismology and has for its purpose the presentation of the fundamental geodynamical foundation of the subject.

The book is written largely after the style of the lectures on which it is based and contains very detailed mathematical deductions. This should render it particularly helpful to the beginning student who wishes to work up by himself the theory of elastic waves in solids, though it will doubtless detract somewhat from the utility of the volume as a reference work and general treatise.

The first quarter of the book is devoted to a thorough review of stress and strain relations in an elastic solid. The employment of Cartesian notation throughout renders the analysis more long winded than necessary. Fortunately the inclusion of a short chapter on the vector treatment somewhat redresses the balance and should indicate to the student the advantage of the dyadic or tensor terminology. So far as the reviewer can ascertain, indeed, it is only in this chapter that a proof is presented for the longitudinal character of plane dilatational waves and the transverse character of plane shear waves, certainly a fundamental matter.

The last three-quarters of the book take up those aspects of elastic wave propagation of importance in seismology, including the two principal types of surface waves on the plane boundary of an elastic solid, *viz.* the Rayleigh and Love waves, respectively. There is also an elaborate discussion of the reflection and refraction of elastic waves at a plane interface, based mainly on the work of Knott and Zoeppritz. This is followed by a theoretical and experimental study of the paths of seismic rays and the bearing of the results on the structure of the interior of the earth. The remaining chapters deal with more practical applications, *viz.*, the interpretation of seismograms, the determination of epicenters, and the depth of focus, i.e., the location of the precise origin of the disturbances resulting in earthquakes. Much of the material summarized is based on the work of the author and his students and is a tribute to the valuable contributions which have been made by them and others in the United States over a considerable period to the important science of seismology.

R. B. LINDSAY
National Broadcasting Company

References to Contemporary Papers on Acoustics

MOST of the titles of papers appearing in other languages than English have been translated. Abstracts in English of many foreign papers have appeared or soon will appear in Science Abstracts, Section A. Where references are made to Science Abstracts, the reference is to the volume number and abstract number.

The numbers appearing at the head of each entry are the numbers which identify the subject headings in the Cumulative Index of this journal issued in November, 1939. This same Classification of Subjects can be found in the index to Volume 16.

Compiled with the generous assistance of Leah E. Smith Librarian, Bell Telephone Laboratories.

2. ARCHITECTURAL ACOUSTICS

2.7 **Sound Waves in Rooms.** P. M. MORSE AND R. H. BOLT. Rev. Mod. Phys. **16**, 69–146 (April, 1944).

2.11 **SL Universal Vibro-Isolator,** absorbs vibration from all directions, which makes it an effective vibration control for diesel engines, generators, panelboards, material-testing equipment, recording apparatus, ventilating and air-conditioning equipment, etc., KORFUND COMPANY. Power **89**, 351 (May, 1945).

4. EAR AND HEARING

4.1 **Functional Examination of Hearing.** A. LEWY AND S. L. SHAPIRO. Arch. Otolaryn. **41**, 220–240 (March, 1945).

4.1 **"Facial Vision;" the Perception of Obstacles by the Blind.** M. SUPA, M. COTZIN, AND K. M. DALLENBACH. Amer. J. Psychol. **57**, 133–183 (1944).

4.2 **Mechanism of the Cochlea.** P. KELLAWAY. Arch. Otolaryn. **41**, 252–260 (April, 1945).

4.2 **Experiments on Conduction of Sound Through the Cavity of the Middle Ear.** H. G. KOBRAK. Arch. Otolaryng., Chicago **37**, 796–801 (1943); also, Stud. Douglas Smith Fdn. **15**, No. 17, 1–16 (1942–1943).

4.2 **Pathways of Transmission to the Cochlea.** P. KELLAWAY. Amer. J. Psychol. **58**, 25–42 (1945).

4.2 **Electrical Cochlear Potentials in Man.** A. M. ANDREER, A. A. ARAPOVA, AND G. V. GERSUNI. Fiziol Ph. SSSR **26**, 205–212 (1939).

4.4 **The Problem of Aviation Deafness. The Airman, his History and his Plane.** P. A. CAMPBELL. Arch. Otolaryn. **41**, 319–321 (May, 1945).

4.4 **Progress of Aviation Otology in World War II.** P. A. CAMPBELL. Arch. Otolaryn. **41**; 381–382 (May, 1945).

4.4 **Speech for the Hard of Hearing.** M. C. NEW. Volta Rev. **47**, 282–284 (May, 1945).

4.4 **Some Modern Trends in the Education of the Deaf.** C. D. O'CONNOR. Volta Rev. **47**, 197–200, 248, 250 (April, 1945).

4.4 **Comparison of Improvement in Hearing Following the Fenestration Operation with that Obtained by Wearing a Hearing Aid.** G. E. SHAMBAUGH. Arch. Otolaryn. **41**, 189–192 (March, 1945).

4.4 **Penicillin—Clinical Use in Otolaryngology.** J. W. FOWLKES. Larnygoscope **55**, 155–163 (April, 1945).

4.4 **Dental Contributions to Otology.** MAYER B. A. SCHIER. Amer. Jour. Orthodontics, Oral Surgery **30**, 750–755 (December, 1944).

4.4 **For References on Deafness** see "Volta Review."

4.5 **The Fitting of Hearing Aids.** R. H. CRUTCHETT. Volta Rev. **47**, 353–354 (June, 1945).

4.5 **A Note on Audiometry.** C. J. GOLLEDGE. Electronic Eng. **17**, 555 (June, 1945).

4.5 **Negative Feed-Back in Hearing Aid Amplifiers.** F. E. PLANER AND E. A. MARLAND. Electronic Eng. **17**, 450–453, 455 (April, 1945).

4.5 **Hearing-Aid Microphone Design.** V. D. EITZEN. Radio News, Radio-Electronic Dept. **4**, 13–15, 30, 32 (May, 1945).

4.5 **The Earpiece—in Testing For and Fitting Hearing Aids.** MAYER B. A. SCHIER. The Laryngoscope (January, 1941).

4.6 **Effect of Barometric Pressure Changes on Hearing.** C. M. KOS. Arch. Otolaryn. **41**, 322–326 (May, 1945).

4.6 **Effect of Aircraft Noise on Hearing.** B. H. SENTURIA. Arch. Otolaryn. **41**, 327–332 (May, 1945).

5. APPLIED ACUOSTICS, INSTRUMENTS AND APPARATUS

5.2 **Cancellation of Even Harmonic Distortion Push-Pull Operation.** G. F. CRAVEN AND G. R. O. VERMEIR. I.R.E. (Australia) Proc. **5**, 12–19 (Jan., 1945).

5.2 **Calibrated Response Curve Tracer.** G. L. HAMBURGER. Wireless Engr. **22**, 170–181 (April, 1945).

5.4 **Harmonic Analysis of Distorted Sine-Waves.** R. C. DE HOLZER. Electronic Eng. **17**, 556–559 (June, 1945).

5.51 **Suggestions for Design of Volume Expanders.** R. W. CRANE. Electronics **18**, 236, 240, 244+ (May, 1945).

5.51 **On an Acoustic Feed-Back in Short Wave Reception with Heterodyne Receivers and Possibilities of Preventing It.** (In German). W. PILTZ. E.N.T. **20**, 17–27 (January, 1943).

5.51 **Studies in Sound.** H. F. OLSON. Radio Age **4**, 12–14 (April, 1945).

5.7 **New Reed Material Minimizes Errors in Frequency Measurement.** D. E. ANDERSEN. Elec. World **123**, 104–105 (May 26, 1945).

5.7 **Frequency Meter with Self-Contained Standard Oscillator.** G. P. ANDERSON. Electronic Eng. **17**, 500–503 (May, 1945).

5.7 **Reed Type Frequency Meter** which operates within the range of 380 to 420 c.p.s. operates on voltage range of 100 to 150 volts. Wirshing Manufacturing Company. Elec. World **123**, 160 (April 14, 1945).

5.7 **Frequency Meter for Use by Factory Personnel.** W. R. STRAUSS. North American Philips Company. Electronics **18**, 150, 152, 154 (May, 1945).

5.8 **A new super power multireflex speaker** designed for extreme long range sound projection over difficult terrain has been announced by University Laboratories. Radio News **33**, 82 (June, 1945).

5.8 **Multi-Reflex Speaker—200w Capacity.** University Laboratories Elec. Equipment **5**, 29 (April, 1945).

5.8 **Electromechanical actuators** weighing as little as 3.05 lb., have been built specifically to meet aviation industry's demand for an efficient method of converting electrical energy into linear actuating force, with least possible weight and size of electromechanical units giving required strength and power. Sear Avia, Inc. Instruments **18**, 271–272 (April, 1945).

5.9 **Moving-Coil Pickup Design.** T. LINDENBERG, JR. Electronics **18**, 108–110 (June, 1945).

5.9 **An Advanced Crystal Pickup Design.** R. DALLY. Radio **29**, 37–38 (May, 1945).

5.10 **Fish Noises.** In order to study systematically the sounds made by fish, Dr. Christopher Coates of the New York Zoological Society Aquarium made oscillograms using an underwater microphone and a cathode-ray oscilloscope. The most immediate application of these results is to aid the crews of sub chasers to distinguish fish noises from the sounds of submarines. Jl. Applied Phys. **16**, 188 (March, 1945).

5.10 **On the Theory of Seismic and Seismoelectric Phenomena in a Moist Soil.** J. FRENKEL. Acad. of Sci. of U.S.S.R. Jour. of Physics **8**, 230 (1944).

5.11 **Audio Oscillator.** Has output of 120 mw. G. E. Company. Elec. Equipment **5**, 15 (May, 1945).

5.13 **Air Terminal Sound System.** W. W. BROCKWAY AND D. C. BROCKWAY. Electronics **18**, 138–141 (June, 1945).

5.13 **Speech Amplifiers. Part VIII—Tone Compensators Using Tuned Circuits.** R. F. SCOTT. Radio-Craft **16**, 491, 523 (May, 1945).

5.16 **The Magnetic Wire Recorder.** H. L. PERDIUE. G. E. Company, N.Y.R.R. Club., Proc. **55**, 140–144 (April 19, 1945).

5.16 **Utah Wire Recorder.** Utah Radio Products Company on Armour license. Radio News **33**, 76 (June, 1945).

5.16 **Magnetic Tape Recording.** Resumé of the development of magnetic tape recording and a description of the Caltron recorder. C. E. WINTER. Radio News **33**, 32–34, 138+ (June, 1945).

5.16 **Magnetic Wire Sound Recorder and Reproducer.** Armour Research Foundation. Includes list of licensed manufacturers. Electronics **18**, 360, 364 (June, 1945).

5.16 **Lear Wire Recorder to Make its Debut.** Radio and Telev. Weekly **59**, 25 (April 4, 1945).

5.16 **Multi-Channel Sound Recording on Film.** Electronic Ind. **4**, 92–93, 158, 159 (April, 1945).

5.16 **Thin Records.** A recent development in plastics and electronics is a wafer-thin Vinylite plastics record, only seven inches in diameter. Each side of the disk will record approximately 15 minutes of dictation. Sound Scriber Corporation, Sci. Am. **172**, 298 (May, 1945).

5.16 **New Standard Tests for Motion Picture Sound Quality.** C. R. KEITH. Internat'l. Projectionist **20**, 22–23 (April, 1945).

5.16 **Recording Discs.** Soundscriber Corporation, Plastics World **3**, 3 (May, 1945).

5.16 **Pocket Model Wire Recorder Designed.** A pocket-sized recorder using wire magnetization with the Armour Research Foundation principles has been designed in an experimental model. Electronic Ind. **4**, 254 (May, 1945).

5.16 **Standardization of the Design and Construction of Wire Recording Equipment.** Electronic Ind. **4**, 122 (May, 1945).

5.16 **Stromberg Engineers Show New Wire Recorder.** The recorder which was shown to engineers representing the civilian licensees of the Armour Research Foundation, reproduced the tones of the musical scale with the highest fidelity yet achieved by the instrument. Telephony **128**, 80 (April 28, 1945).

5.16 **Duotone Company** has announced the availability of several hundred Van Eps cutting heads. Radio News **33**, 78 (May, 1945).

5.16 **Notes on Distortion in Phonograph Reproduction Caused by Needle Wear.** B. B. BAUER. Acoustical Soc. Am. Jl. **16**, 246–253 (April, 1945).

5.16 **Sound Reproduction Standards.** Brief note. Electronics **18**, 326 (May, 1945).

5.16 **Sound Recorder Employs Microphone and Magnetic Wire.** Radiotechnic Laboratory Ind. Equip. News **13**, 75 (May, 1945).

5.16 **Recording Unit.** Robinson-Houchin Optical Company, Electronics **18**, 346 (May, 1945).

6. MUSICAL INSTRUMENTS AND MUSIC

6.1 **The Effect of Music on Visual Acuity.** A. DANNENBAUM. Sarah Lawrence Stud. **4**, 18–26 (1945).

6.1 **Certain Applications of Physical Principles to the Playing of Musical Instruments.** W. F. G. SWANN. Franklin Inst., Jl. **239**, 163–184 (March, 1945).

6.7 **Tone Quality of the Violin Observed Closely with the Cathode Ray Oscillograph.** F. HOIGNÉ. Neuen Zürcher Zeitung. Beilage Technik. No. 1729 (Nov. 3, 1943).

8. STANDARDS

8.1 **New Data in Revised Standard for Sound Level Meters.** Ind. Standardization **16**, 68 (March, 1945).

9. SPEECH AND SINGING

9.3 **Altitude Affects Speech.** Stratosphere flyers may have difficulty in speaking so that others in the crew can understand them over their interphones. Sci. News Letter **47**, 230 (April 14, 1945).

10. SUPERSONICS (ULTRASONICS)

10.3 **Natural Elastic Vibrations of a Right-Angled Parallelopipedon of Quartz.** (In German.) R. BECHMANN. Zeits. f. Physik **122**, 510–526, nos. 5–8 (1944).

10.3 **Terminology of Interpenetrating Twins in Alpha-Quartz.** Letter to the editor, Nature **155**, 424 (April 7, 1945).

11. WAVES AND VIBRATIONS

11.3 **An Experimental Determination of the Velocity of Sound in Dry CO_2-Free Air and Methane at Temperatures Below the Ice Point.** Phys. Rev. **67**, 298–303 (May 1 and 15, 1945).

11.3 **"Second Sound" in Helium II.** Letter to the Editor. V. PESHKOV. Acad. of Sci. of U.S.S.R., Jour. of Physics **8**, 381 (1944).

11.5 **Audible Audio Distortion.** H. H. SCOTT. References. Nat'l Electronics Conf., Proc. **1**, 138–145 (1944).

11.7 **Natural Elastic Vibrations of a Right-Angled Parallelopipedon of Quartz.** (In German.) R. BECHMANN. Zeits. f. Physik **122**, 510–526, nos. 5–8 (1944).

11.7 **Harmonic Analysis of Distorted Sine-Waves.** R. C. DE HOLZER. Electronic Eng. **17**, 556–559 (June, 1945).

11.7 **Vibration Testing—First Step in Improving Ruggedness.** Elec. Mfg. **35**, 115–117, 194+ (April, 1945).

11.7 **Propagation of Elastic Waves in a Solid and Propagation of Symmetrical Components in a Three-phase System.** (In French.) M. Parodi. Jl. de Physique **4**, 67–70 (April, 1943).

11.7 **Improved Methods for Calculating Torsional Vibration. I. References.** R. H. SCANLAN. Mach. Design **17**, 159–162 (April, 1945).

11.7 **Uniform Relationship Between Sinusoids, Relaxation Vibrations and Relaxation Discontinuities.** (In German.) W. Reichardt. E.N.T. **20**, 213–225 (Sept. 1943).

11.7 **Calculation of Roots of Square Sums and Differences with the Slide Rule.** (In German.) E.T.Z. **64**, 145–146 (April, 20, 1944).

Review of Acoustical Patents

ROBERT W. YOUNG
C. G. Conn, Ltd., Elkhart, Indiana

Patents reviewed below have been issued by the United States Patent Office on the dates indicated. Printed copies may be obtained from the Commissioner of Patents, Washington, D. C. at a cost of 10¢ each. Remittance may be made by money order, check, cash, or special coupons which are sold in blocks of twenty or books of one hundred.

The decimal numbers appearing before titles are those which identify the headings being used in the analytic subject index of this journal. The Patent Office classification given in parentheses with each patent entry is outlined in the "Manual of Classification of Patents" which is obtainable from the Superintendent of Documents.

The opinions expressed are those of the individual reviewers only.

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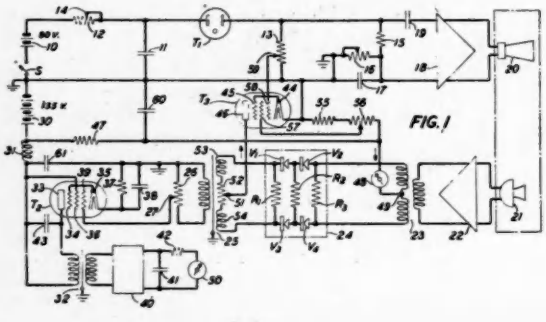
2,370,385
2.7 METHOD OF ACOUSTIC MEASUREMENT AND APPARATUS THEREFOR

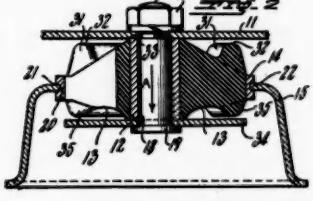
Leonard G. Abraham and Doren Mitchell, assignors to Bell Telephone Laboratories, Incorporated.
February 27, 1945, 9 Claims, (Cl. 181–0.5).

A specific application of this invention is testing a room in which microphone and loudspeaker are to be installed for loud-speaking telephone conferences. "These instruments must be so located with respect to each other that singing is prevented and that echoes from walls or other acoustic reflectors do not confuse the intelligible transmission of speech uttered in the room. It is found by experience that echoes later than the first are progressively more disturbing, from which it appears that the subjective judgment of the suitability of a room involves a spontaneous although perhaps unrecognized weighting of the echoes wherein greater and greater weights are assigned to the successively later echo components." The dashed line in the figure typifies the room being tested. A relaxation oscillator supplies a pulse of 10 milliseconds duration to loudspeaker **20** and at the same time biases T_3 to cut-off. As a consequence, the d.c. current through varistors V_1, V_2, V_3, V_4 becomes small and their impedance to a.c. is increased. Thus the direct sound pulse picked up by microphone **21** affects the reading of meter **50** only slightly. However, as the bias on grid **58** decays the varistors again become conducting so that echoes which are late in arriving at microphone **21** are weighted more heavily than those which immediately follow the direct sound. The cycle is repeated every half-second and, since the time constant of resistor **42** with condenser **41** is 25 seconds, the reading of meter **50** soon acquires a steady value which is a function of the weighted echoes.—RWY.



2,375,105
2.11 RESILIENT MOUNTING

Heston H. Hile, assignor to United States Rubber Company.
May 1, 1945, 3 Claims (Cl. 248–358).

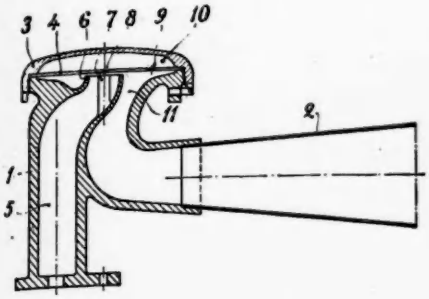


The resilient mounting presented may be easily removed from and attached to the base **15** by radially compressing the outer member **14** which is made in the form of a split ring.—DBS

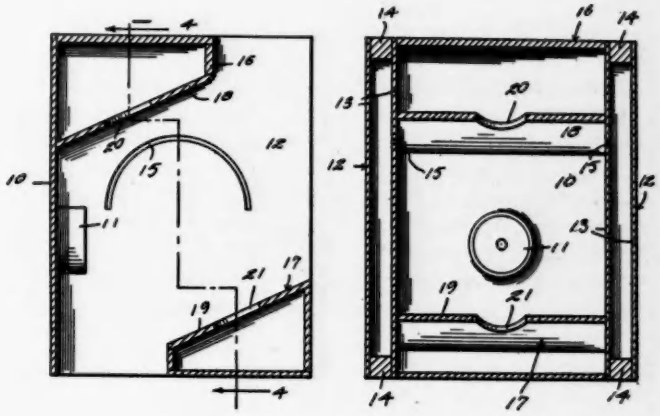
2,371,949
5.1 ACOUSTIC ALARM DEVICE

Sven Agne Bjergel, assignor to Telefonaktiebolaget L. M. Ericsson.
March 20, 1945, 6 Claims (Cl. 177–7).

"When the acoustic alarm device is to give signals, air is supplied to the supplying channel **5**. Air thereby will flow out between the diaphragm **4** and the seat **6** through the passage **11** and horn **2**. Simultaneously the air will flow through the hole **8** of the diaphragm into the chamber **10**.



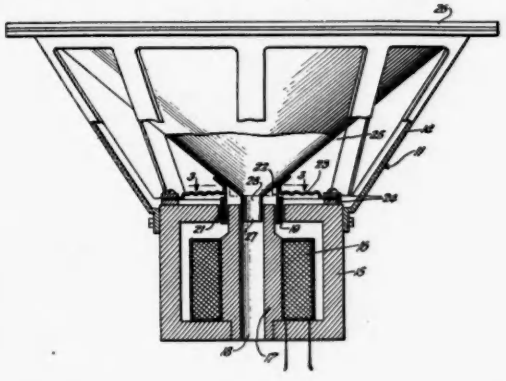
The air pressure above the diaphragm thereby will increase, thus pressing the latter against the seat **6**. The plug **7** in the supplying channel **5** now completely covers the hole **8** in the diaphragm. Consequently, the air will be prevented from flowing further into the chamber **10** and thus the pressure in the same will decrease, as air is coming out through the hole **9** of the diaphragm. When the total pressure on the upper side of the diaphragm becomes equal to or less than the total pressure of the air, which is flowing in through the channel **5** on the lower side of the diaphragm, the latter returns to its initial position."—FHS



Sound boxes with holes in them, and vibrating plywood panels with arc-shaped slots all, according to the inventor, contribute to "perfect clarity of tone . . . volume without distortion, a lack of harshness, greater carrying power. . . . The quality of the loudspeaker or the electrical input to the speaker are completely ignored.—FHS

2,367,026
5.8 ELECTRODYNAMIC SPEAKER

William H. Hutter, assignor to Rock-Ola Manufacturing Corporation.
January 9, 1945, 3 claims (Cl. 179–115.5).



To prevent the accumulation of dirt in the apex of the cone when the speaker is mounted with its cone opening upward, the speaker described in this patent is made with a tubular opening **27** at the cone apex. This tube slides into the bore **18** which extends completely through the central pole piece **17**.—FHS

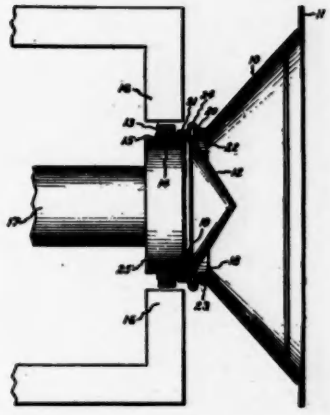
2,368,639
5.8 TONE CHAMBER

Frank C. Carter, assignor to Florence Carter.
February 6, 1945, 8 Claims (Cl. 181–27).

2,371,951
5.8 DOUBLE DIAPHRAGM LOUDSPEAKER

Ellsworth D. Cook, assignor to General Electric Company.
March 20, 1945, 2 Claims (Cl. 179–115.5).

The compliant element **24** allows the voice coil **13** and the inverted cone **12** to vibrate at high frequencies without



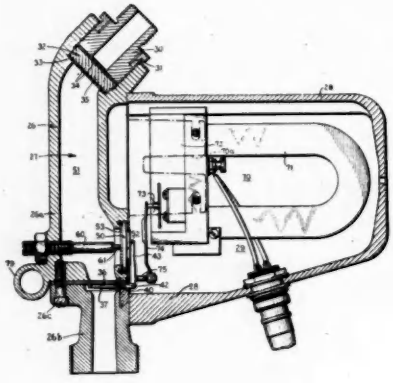
the large cone **10** adding too large a mass load to the vibrating system. At low frequencies both cones move together to provide a larger radiating area.—FHS

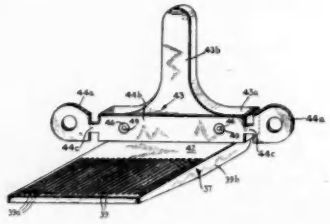
2,371,960

5.8 SOUND PRODUCING DEVICE

William C. Eaves, assignor to Eaves Sound Projectors, Incorporated.
March 20, 1945, 7 Claims (Cl. 179–108).

A loudspeaker unit employing a modulated air stream is described in this patent. The air stream enters the unit at coupler **30**, flows through the modulating valve **36** and **37**, and out through **26b** into a horn. The constant air pressure on the valve gate **37** is balanced by a similar pressure on





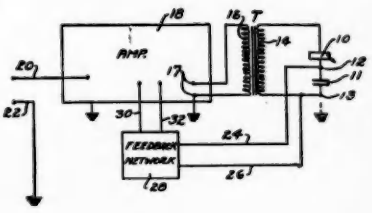
diaphragm **50**. The diaphragm and the valve gate are connected by arm **43** and a pressure block **52** made of some non-resonant material such as rubber or cork. Some sort of driving means **70** actuates the valve gate through links **73**, **74** and **75**.—FHS

2,372,956

5.8 FEED-BACK CIRCUIT

Stanley R. Jordan.
April 3, 1945, 4 Claims (Cl. 179–100.4).

This patent proposes to minimize the temperature effect in Rochelle salt crystal motors by applying negative voltage feedback to the driving amplifier, said feedback voltage being derived from a condenser of substantially zero tem-



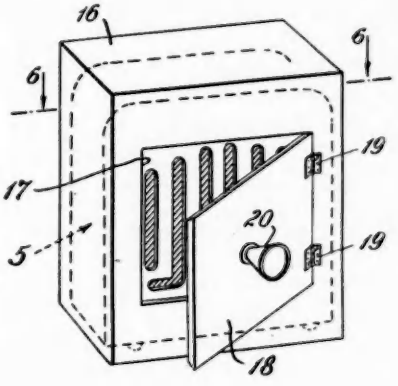
perature coefficient placed in series with the crystal motor. This tends to keep the charge on the crystal constant.—LWS

2,373,172

5.8 MUFFLER FOR INTERCOMMUNICATING SYSTEM UNITS

William Sinkler Darby.
April 10, 1945, 6 Claims (Cl. 179–1).

This device is intended to reduce the noise pick-up when an intercom substation is located in a noisy place. A conventional dual purpose microphone-loudspeaker, such as ordinarily used in intercom systems, is housed in case **5**. Surrounding this case is another case **16**. In the front of case **16** is a door **18** which is mounted on spring hinges **19**.



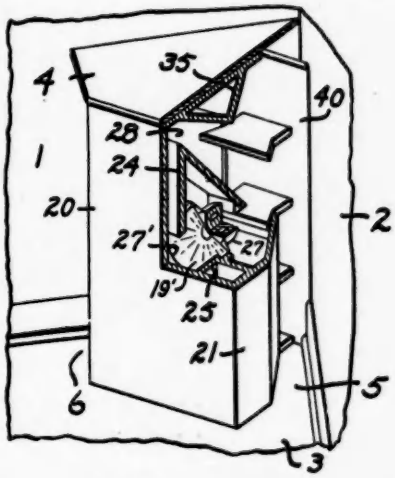
The springs hold the door open so not to interfere with the normal action of the loudspeaker, but when a person is using the combination microphone-loudspeaker as a microphone the door may be closed to prevent the pick-up of noise. To allow the sound of the voice to get through the door there is a hole cut in it and a speaking tube **20** is mounted in the hole.—FHS

2,373,692

5.8 LOUDSPEAKER

Paul W. Klipsch, assignor of twenty percent to Ray L. Smith.
April 17, 1945, 22 Claims (Cl. 179–1).

The loudspeaker described is a folded low frequency horn. It is intended, primarily, to be used in the corner of a



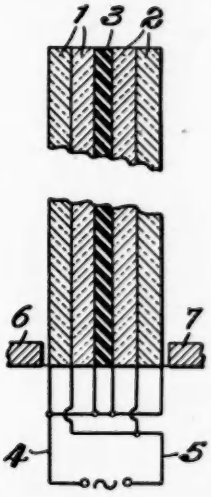
room in such a way that the wall and floor surfaces form part of the horn boundaries. See P. W. Klipsch, J. Acous. Soc. Am. **13**, 137 (1941) and P. W. Klipsch, J. Acous. Soc. Am. **14**, 179 (1943) for a complete description of this horn.—FHS

2,368,609

5.9 ELECTROACOUSTIC TRANSDUCER

Ernst Burkhardt, assignor to General Electric Company.
January 30, 1945, 8 Claims (Cl. 171–327).

By combining two or more "bimorph" piezoelectric crystals **1**, **2** with intermediate layers **3** of rubber-like material it is possible, the inventor states, to obtain a crystal

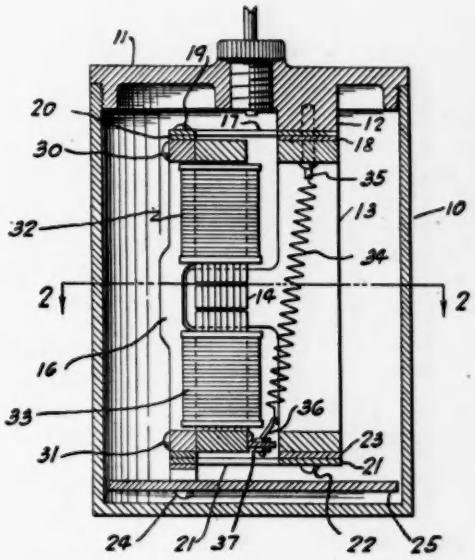


structure with a much lower resonant frequency than the conventional construction permits.—FHS

2,371,973

5.10 GEOPHYSICAL PROSPECTING APPARATUS

John P. Minton, assignor to Socony-Vacuum Oil Company, Incorporated.
March 20, 1945, 1 Claim (Cl. 177–352).



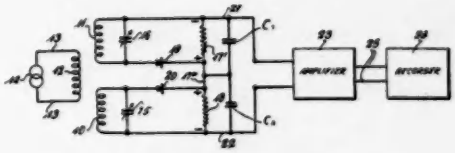
This patent covers the modulator type of pick-up using two variable inductances in a Wheatstone type a.c. bridge as illustrated.—GWD

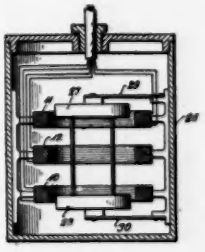
2,372,056

5.10 METHOD AND APPARATUS FOR RECORDING SEISMIC WAVES

Robert A. Broding, assignor to Socony-Vacuum Oil Company, Incorporated.
March 20, 1945, 9 Claims (Cl. 177–352).

A translating system is shown using a modulator type pick-up device and an electric circuit to effect the demodulation. Two resonant circuits **11**, **16** and **10**, **15** are loosely coupled to primary **12**. Iron slugs **27** and **28** move relative





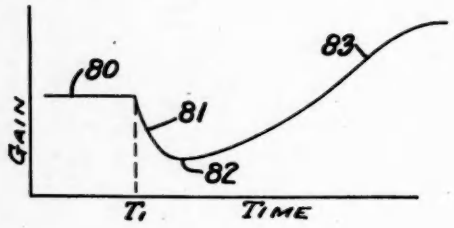
to the coils under influence of acceleration so the resonant frequency of one circuit increases as the other decreases. The carrier voltage **14** inserted at **12** is thus modulated in proportion to the relative motion of the slugs.—GWD

2,374,204

5.10 APPARATUS FOR RECORDING SEISMIC WAVES

Herbert Hoover, Jr., assignor to United Geophysical Company.
April 24, 1945, 7 Claims (Cl. 177–352).

This invention covers methods of controlling the gain of seismograph amplifiers according to the time function plotted in the figure. "Recording the initial portion of a seismic wave train at intermediate sensitivity has many

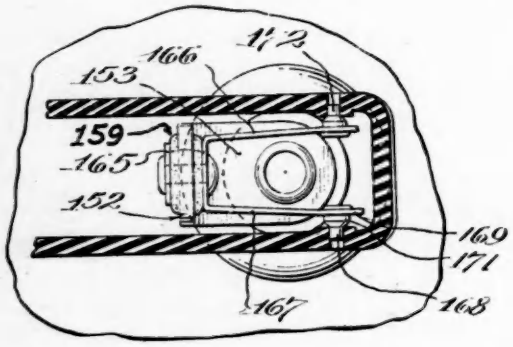


advantages, among which are the production of quiet traces prior to the reception of the seismic waves, and the production of sharp first breaks in the record."—GWD

2,363,655

5.16 TONE ARM

Roy Dally, assignor to Webster Electric Company.
November 28, 1944, 1 Claim (Cl. 274–23).



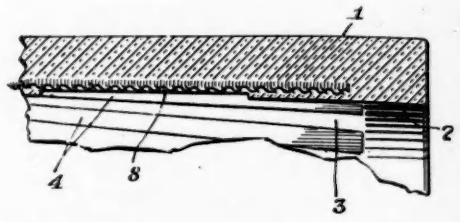
This phonograph tone arm features a resilient grommet **159** for mounting the tone arm to the pivot.—LWS

2,364,545

5.16 PHONOGRAPH RECORD

James W. Nell, assignor to Thomas A. Edison, Incorporated.
December 5, 1944, 4 Claims (Cl. 274–44).

This patent describes a method for reenforcing a "wax" record by a material having considerable nap such as



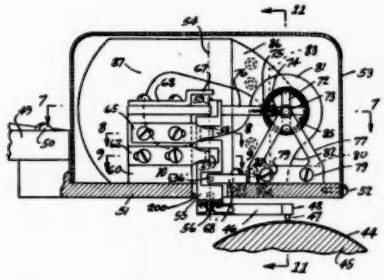
flannel. The material is sized before molding in a medium composed of metallic soap and a fatty acid as a diluent and thinned by a solvent such as zylene.—LWS

2,367,846

5.16 SOUND RECORDING AND REPRODUCING APPARATUS

Albert W. DeSart, Sr., assignor to United Acoustigraph Corporation.
January 23, 1945, 11 Claims (Cl. 179–100.41).

This moving coil phonograph recording head features a multiple knife edge support for the stylus arm, the indi-



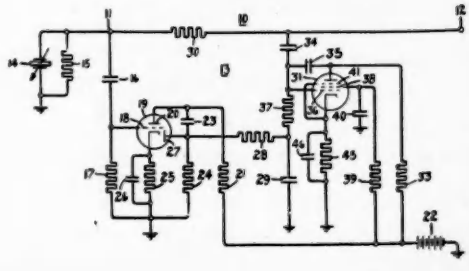
vidual knife edges **56, 57, 58, 59** being angularly displaced from each other about the longitudinal axis **54** of the support.—LWS

2,369,952

5.16 BACKGROUND NOISE SUPPRESSOR

George F. Devine, assignor to General Electric Company.
February 20, 1945, 8 Claims (Cl. 179–100.4).

This background noise suppressor circuit utilizes reactance tube **31** as the capacity element of a R–C low pass filter section comprised of series resistor **30** and the shunt capacity of tube **31**. The circuit is so designed that the



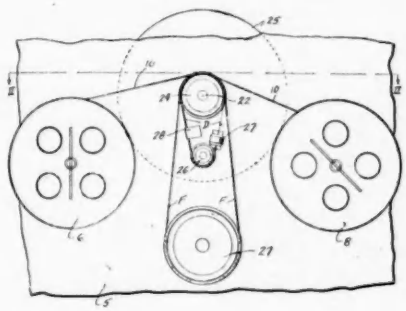
effective capacity is a function of the signal frequency and also its magnitude. Thus when there are no high frequencies present in the record, the by-passing action is large and the high frequency background noise is suppressed; when high frequencies are present in a loud passage the increased potential derived from anode **27** of tube **19** decreases the by-passing action of tube **31**.—LWS

2,372,810

5.16 CONSTANT SPEED DRIVE FOR MAGNETIC RECORDERS

Marvin Camras, assignor to Armour Research Foundation.
April 3, 1945, 7 Claims (Cl. 179–100.2).

In this constant speed drive for a wire recorder the wire passes over drive pulley **24**, then over large idler **27**, back over **24**, next around small idler **26**, then to **24**, again to

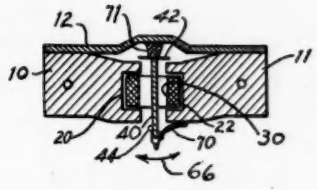


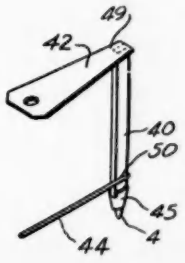
27, finally over **24** and to the take-up reel **8**. Sound is recorded or reproduced by device **28**. Large flywheel **25** is included to smooth our irregularities.—LWS

2,373,181

5.16 TRANSDUCER

Lawrence Fleming.
April 10, 1945, 7 Claims (Cl. 179–100.41).





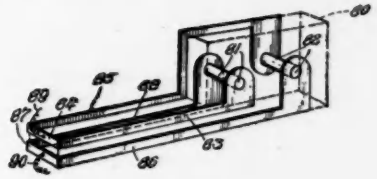
The light armature **40** of this electromagnetic phonograph reproducer passes through coil **30** which lies in recesses in pole tips **10** and **11**. The combination of the flat spring **42** and the wire spring **44** allows the stylus **4** to move in the lateral and vertical directions but constrains it from motion in the direction of the groove. Lateral and vertical damping are provided by Viscoloid blocks **70**, **71**, respectively. See J. Acous. Soc. Am. **12**, 366–373 (1941).—LWS

2,373,676

5.16 REPRODUCER

Kenneth J. Germeshausen.
April 17, 1945, 9 Claims (Cl. 179–100.4).

This phonograph reproducer employs strain sensitive coatings, such as graphite on a beam of insulating material **80**. The stylus is attached below **87**. By providing two strips of conducting material **83**, **86**, **85**, **88** on each side of the



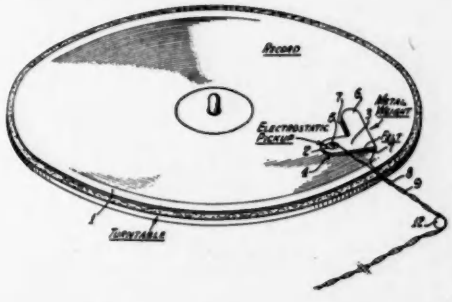
beam a bridge circuit with four active elements is formed. Battery current is supplied across bridge corners **81**, **82** and corners **89**, **90** are connected to the grids of a push pull amplifier through a suitable blocking condenser.—LWS

2,374,785

5.16 RECORD REPRODUCING SYSTEM

Chester M. Sinnett and Rene Snepvangers, assignors to Radio Corporation of America.
May 1, 1945, 16 Claims (Cl. 179–100.4).

The conventional phonograph reproducer tone arm is eliminated by mounting the reproducer in a metal weight **3** which is supported directly on the record by felt pad **7**.



Motion tangential to the groove is constrained by transmission line **8**, **9**; radial motion is permitted by securing said line to pivot **12**. The line thus replaces the usual tone arm and the pivot is in the usual position, not as shown in the figure.—LWS

2,371,453

5.17 TELEPHONE UNIT

Charles S. Linell, assignor to Frank Raffles.
March 13, 1945, 8 Claims (Cl. 179–114).

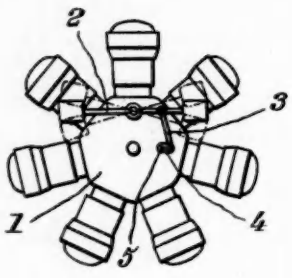
This patent describes a rather thin telephone receiver. The claims are quite limited.—FHS

2,154,359

5.21 DEVICE FOR BALANCING RECIPROCATING ENGINES

Raoul Roland Raymond Sarazin.
April 11, 1939, 8 claims (Cl. 74–604).

This invention relates to devices for balancing reciprocating engines subjected to reciprocating couples. In one of its simpler forms it consists of a counter-balance device

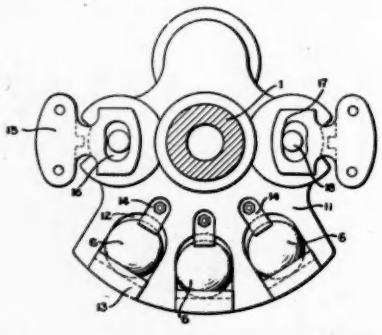


2 pivoted on the engine crankcase 1 and driven at an appropriate frequency by means of the crank 4 and link 3.—DBS

2,313,024

5.21 DEVICE ADAPTED TO ELIMINATE OSCILLATIONS

Francois Marie Michel Bernard Salomon; vested in the Alien Property Custodian.
March 2, 1943, 11 Claims (Cl. 74–604).



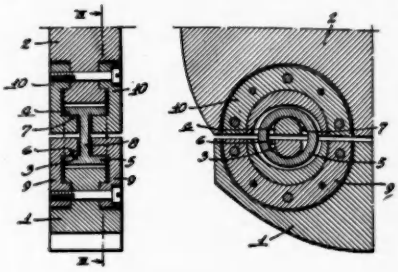
The device described employs centrifugal pendulums to suppress both torsional and transverse vibrations. Transverse vibration is suppressed by use of a pendulum 6 in the form of a solid sphere free to oscillate in a plane parallel to the axis of the shaft.—DBS

2,356,435

5.21 VIBRATION DAMPER

Raoul Roland Raymond Sarazin; vested in the Alien Property Custodian.
August 22, 1944, 5 claims (Cl. 74–574).

This invention describes a suspension system for centrifugal pendulum dampers in which the pendulous mass 1 is suspended by means of convex runways 3 and 4 and the



rolling body 5. The inventor considers this type of suspension superior to the more conventional type in which the pendulous mass is carried on pins having external rolling surfaces.—DBS

2,361,349

5.21 VIBRATION INDICATOR

Radford K. Frazier, assignor to Bendix Aviation Corporation.
October 24, 1944, 2 Claims (Cl. 73–67).

This simple device utilizes persistence of vision for indication of vibration amplitude. It consists of a triangular shaped figure 3 and a scale 2. Vibration in the plane of the

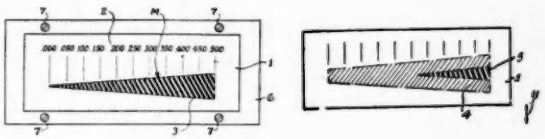


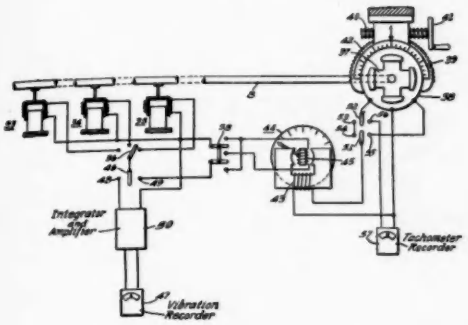
figure produces a modified figure 5 due to persistence of vision. The altitude of the modified triangle 5 is proportional to the amplitude of vibration.—DBS

2,363,373

5.21 SHAFT VIBRATION PICK-UP

Harry C. Werner, assignor to Westinghouse Electric and Manufacturing Company.
November 21, 1944, 9 Claims (Cl. 171–209).

This invention relates to permanently mounted vibration and recording apparatus for continuously measuring and recording turbine shaft vibration. The outputs of moving coil pick-ups 33, 34, 35, which are proportional to the lateral shaft vibration, are combined with the output of a rotatable stator sine wave generator 38 and fed to wattmeter 44.



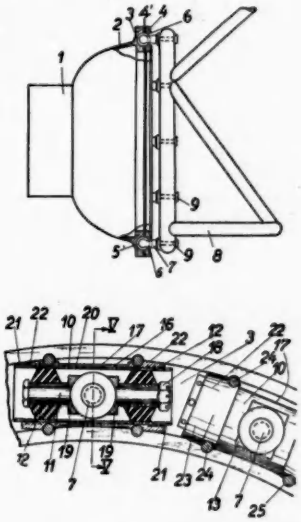
The wattmeter reading and the adjusted position of the stator **42** are indications of the amplitude and phase angle of the turbine shaft vibration.—DBS

2,369,077

5.21 VIBRATION DAMPING SUSPENSION

Hans Joachim Seidel; vested in the Alien Property Custodian.
February 6, 1945, 5 Claims (Cl. 248–5).

This invention describes a power plant suspension in which sleeve type rubber springs **5** are carried as an integral part of the engine crankcase **2**. The inventor points out



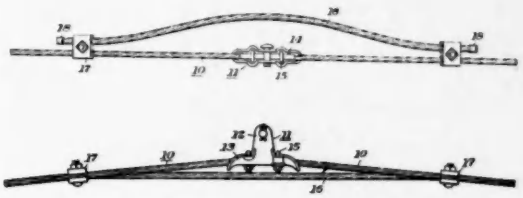
that by use of this type of mounting the power plant can be designed from the first so that no resonant vibrations of the power plant occur within the operating speed range.—DBS

2,374,823

5.21 VIBRATION DAMPER FOR SUSPENDED WIRES AND CABLES

Francis E. Leib and Harold R. Wilbur, assignors to Copperweld Steel Company.
May 1, 1945, 7 Claims (Cl. 174–42).

The vibration damper presented is extremely simple and consists only of a length of cable **16** fastened to the suspended cable **10** by use of two clamps **17**. Means for apply-



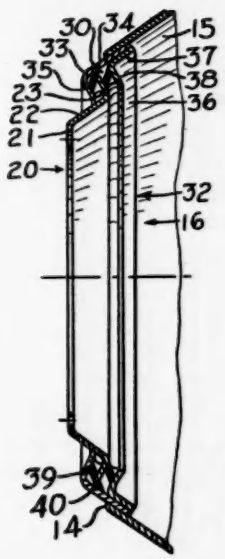
ing the damper to the dead-end of a cable is also disclosed. It is claimed that the device is effective in eliminating resonant vibration or "galloping" of transmission lines.—DBS

2,377,006

5.21 FLEXIBLE ENGINE MOUNT

Edward H. Heinemann and Paul A. Dennis, assignors to Douglas Aircraft Company, Incorporated.
May 29, 1945, 9 Claims (Cl. 248–5).

This invention relates to a flexible engine mount for attaching radial aircraft engines to airframe structures. The engine mounting ring **20** is fastened to the forward end of the monocoque airframe **15** by use of annular elements **33**



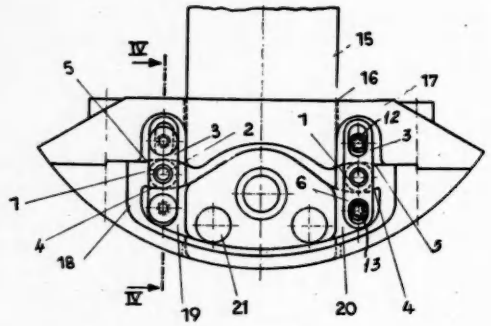
and **36** and vibration dampening material **30**, securely bonded to the annular elements and the mounting ring.—DBS

2,378,592

5.21 CRANKSHAFT FOR INTERNAL COMBUSTION ENGINES

Otto Specht; vested in the Alien Property Custodian.
June 19, 1945, 6 Claims (Cl. 74–604).

This invention describes a particular form of the "bifilar" centrifugal pendulum suspension in which the rollers **1** are maintained in definite relationship with the runways **4** and



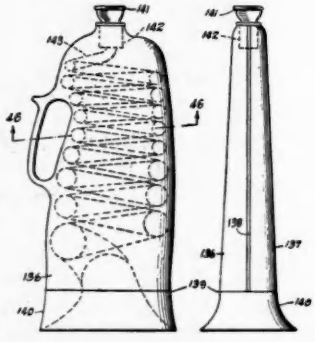
5 by means of links 3. The inventor claims this device to be advantageous in the case of pendulums tuned to low orders.—DBS

2,373,110

6.3 WIND INSTRUMENT

Carl F. W. Forssberg.
April 10, 1945, 6 Claims, (Cl. 84–387).

In a manner reminiscent of the "sausage-bassoon" the convolutions of this bugle are concealed within two pieces of plastic **136**, **137**, cemented together. A partition **138** separates the passageways which alternate from one side to



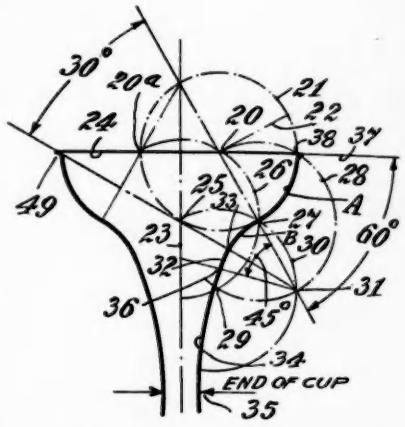
the other. The bell **140** may be molded separately. Also disclosed is a cornet in which the valves are incorporated within the same general form shown in the figure.—RWY

2,376,453

6.3 MOUTHPIECE FOR CORNETS

Justin Ruettiger.
May 22, 1945, 4 Claims (Cl. 84–398).

The cup of this mouthpiece for a cornet is characterized by a portion A whose center of curvature **20** is in the plane



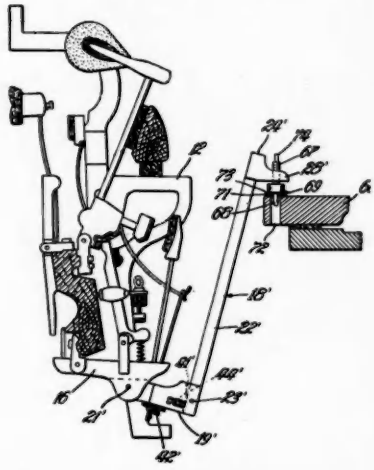
of the rim and whose radius of curvature **22** is one-third the diameter at the rim. Portion B may have the same radius but with center indicated in the figure. A "constant curve" from **33** to **35**, of shape not definitely specified, completes the cup.—RWY

2,367,192

6.6 PIANO ACTION

William G. Betz, assignor to Pratt, Read & Company.
January 16, 1945, 17 Claims (Cl. 84–240).

In this drop action for piano the head **74** of the adjusting screw **67** is quite accessible. A substantial bearing surface is provided where this screw contacts bushing **71**. When the



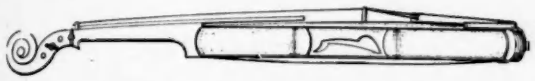
action is removed from the piano the abstract is prevented from falling outward by rest rail **42'** and spring **44'**.—RWY

140,294

6.7 DESIGN FOR A VIOLIN

Edgar Garding.
February 6, 1945 (Cl. D56–1).

In this violin the usual *f*-holes are replaced by openings such as illustrated in the figure. It would appear that the

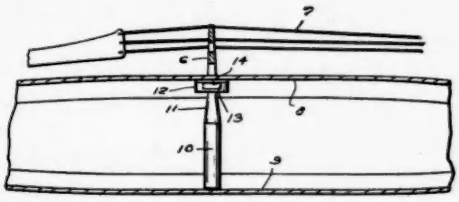


draftsman took some liberty with other proportions of the instrument.—RWY

2,370,460
6.7 TONE POST FOR VIOLINS AND SIMILAR MUSICAL INSTRUMENTS

John Bell.
February 27, 1945, 5 Claims (Cl. 84–277).

This sound post **10** for a violin is in the shape of a *T*. The head of the *T* is hollowed out so as to make it somewhat yielding to vertical motion from the bridge. The purpose of this is to "improve the flexibility, tone filtration and per-

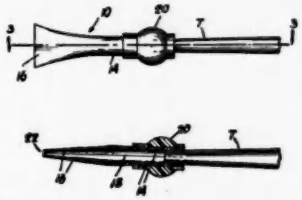


ceptible overtone by setting up tonal vibrations which have a tendency to improve the sound qualities of the instrument." In practice, the parts **12** and **14** may be made of pieces of bamboo.—RWY

2,374,579
6.8 DOUBLE REED

Arnold Brilhart, assignor to Arnold Brilhart Ltd.
April 24, 1945, 3 Claims (Cl. 84–383).

A cylindrical portion **14** is formed in this plastic bassoon reed by cementing together two blades **16** along the edges **18** of the semi-cylindrical parts molded as integral parts thereof. Consequently without special reaming the reed fits over the end of mouthpipe **T**. The enlargement **20**, which

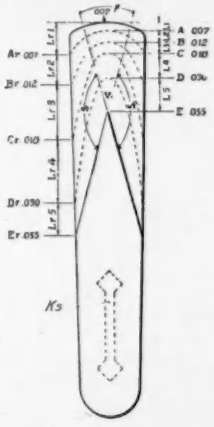


is molded separately, constitutes a fingerhold and reenforcement. Oboe reeds are made similarly with a cylindrical part. Thus the tube to which the oboe reed is attached does not have to be flattened in the way usually necessary for cane.—RWY

2,375,934
6.8 REED

Stephen J. Lucas.
May 15, 1945, 2 Claims (Cl. 84–383).

"The particular object of this invention is to provide a reed of definite structural features and dimensions which can be produced in dies from plastics and mounted in accurate coacting position on the mouthpieces of instruments, to produce sound waves of improved quality and amplitude with the least expenditure of energy." A gen-

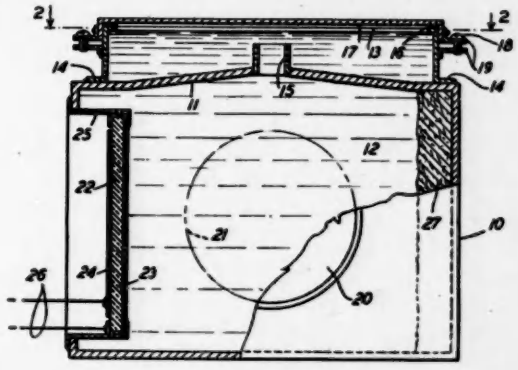


eral characteristic of these reeds for woodwind musical instruments is a thickness of about 0.045 inch at the portion **V** thence tapering to about 0.006 to 0.008 inch at the vibrating edges. The key slot **Ks** on the under side of the reed mates with a corresponding key on the mouthpiece. A baritone saxophone reed is illustrated.—RWY

2,366,822
10.2 ULTRASONIC CELL

Gerald W. Willard, assignor to Bell Telephone Laboratories, Incorporated.
January 9, 1945, 2 Claims (Cl. 88–61).

"An object of the invention is to provide an improved form of liquid ultrasonic cell in which that portion of the cell through which compressional waves are propagated is kept filled with liquid at substantially constant pressure irrespective of the orientation of the cell and volume changes



of the liquid." Compressional waves originate at crystal **22** and are absorbed at pad **27**. An upper auxiliary reservoir has an air space **13** by which the pressure is maintained essentially constant in the liquid if the latter expands or contracts.—RWY